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W. B. No. 583.
U. S. DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU.
CHARLES F. MARVIN, Chief.

WEATHER FORECASTING IN THE UNITED STATES.

BY A BOARD COMPOSED OF

ALFRED J. HENRY, Chairman.
EDWARD H. BOWIE.
HENRY J. COX.
HARRY C. FRANKENFIELD.

WASHINGTON
GOVERNMENT PRINTING OFFICE
1916

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U.S. Department of Agriculture.

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PREFACE.

The initiative that led to the production of this work is due to Prof. Charles F. Marvin, Chief of the Weather Bureau, who, in November, 1913, addressed the following letter to the forecasting staff of the bureau:

SIR: Although the Weather Bureau has been successfully forecasting the weather for many years it is a rather notable fact that scarcely anything has been written to explain, more or less fully and in detail, the processes by which good forecasts can be made, and it is desired to prepare, for the guidance and instruction of beginners, some sort of textbook or manual covering existing knowledge of this important subject. The character of the publication is perhaps indicated by the following suggested titles:

"Theory and Practise of Forecasting the Weather in the United States."

"Manual of Weather Forecasting in the United States."

"Rules for Forecasting the Weather in the United States."

It is recognized that at the present time even the best forecasting rests upon a more or less empirical basis, nevertheless it seems proper to bring together, in the publication contemplated, a comprehensive presentation of the knowledge and experience of the best forecasters of the Weather Bureau.

You are, therefore, requested to submit an essay on the subject, setting forth according to your own ideas and to the fullest possible extent the general rules and considerations that guide you in your forecast work, illustrating the matter by reference to standard types of weather maps, or even by imaginary or representative conditions as shown by weather maps.

In order that the work may be coordinated as fully as possible the essays should perhaps be prepared along certain similar lines, such, for instance, as specific rules for making forecasts, either for certain conditions of the weather or for certain sections of the country located in some particular area in relation to the meteorological conditions. The discussion should perhaps treat the subjects of weather, temperature, storm conditions, frosts, etc., separately, as it seems that such a classification would facilitate the consolidation of ideas and future study of the subject.

The foregoing are only general suggestions. The chief object is to get from those most highly trained in the art the fullest possible statement of how weather forecasts can be made. It is proposed to combine and consolidate the information that may be received, and every effort will be made to give full credit to the individual contributors, either separately, in the case of specific rules emanating only from the individual, or severally, where substantially the same precepts are expressed by more than one.

In accordance with the foregoing, it is suggested that the subject be treated under the following separate headings:

1. Weather and temperature forecasts.
2. Storm warnings.
3. Cold waves.
4. Special frost forecasts for restricted localities.

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Furthermore, as actual practice forecasts are made for States and small districts, it seems proper that the discussion should be related to those geographic areas.

The rendition of the essay requested is optional.

Very respectfully,

(Signed) C. F. MARVIN,
Chief of Bureau.

On August 31, 1914, a board was formed for the purpose of arranging the material of the essays received in consequence of the above letter in the form of a handbook or manual that could be published and distributed among the officials of the Weather Bureau for their guidance in qualifying themselves in the art of forecasting.

It seemed to the board that the most satisfactory method of accomplishing the desired result, and, indeed, the only feasible one that presented itself, would be for the board to undertake through the individual efforts of its members the joint preparation of a handbook. Such a plan, though it has its limitations and is not entirely without objectional features, was approved and the work of preparing the different chapters was immediately begun. As these were prepared simultaneously, without conference or consultation, the work unavoidably lacks the unity of treatment that would have resulted from individual authorship.

The introductory chapters treat of the general circulation of the atmosphere. The fourth chapter is devoted to changes in atmospheric pressure as graphically shown on the auxiliary pressure-change charts of the Weather Bureau, and their significance in forecasting. In the fifth chapter an attempt has been made to present in a very general way the observed association of weather phenomena with the different forms of HIGHS and LOWS of the weather map, and the changes due to a shifting of the relative position of these HIGHS and LOWS with respect to each other. Chapters VI, VII, VIII, and IX are devoted to the forecasting of special phenomena of the weather, such as cold waves, frosts, high winds, heavy snow, sleet and ice, storms, fog, and thunderstorms. Chapters X, XI, and XII are devoted to the forecasting of what may be called the daily routine of wind and weather—from a consideration of the different weather types that overspread the district.

There will be found throughout a large part of this work more or less repetition of the same thought, though perhaps in a slightly different setting. While it has been the endeavor of the board to present only those precepts upon which there is substantial agreement, the discerning reader will doubtless find a few cases in which the precepts given may be differently interpreted. In all such cases the weather maps alone must be the final arbiter as between the deductions of individuals.

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The book will be a disappointment to those, if there be such, who have formed the expectation that it will solve the difficulties of the forecasting problem. The consensus of opinion seems to be that the only road to successful forecasting lies in the patient and consistent study of the daily weather maps. Wherein the book will be helpful, however, is in the fact that it gives the experience of those who have gone before, and it is in this sense that it will find its most useful application.

ACKNOWLEDGMENTS.

The board desires to acknowledge its indebtedness to Prof. Charles F. Marvin, whose unfailing support has made the work possible; to Prof. William J. Humphreys, who contributed the chapter on the "General circulation of the atmosphere;" to the district and the local forecasters who contributed essays, and to Mr. Edward C. Easton for the excision of many awkward English constructions.

Acknowledgments are also due to that small group of civilian officials, who, with the Army officers that were detailed to duty with the Signal Service during the period 1871–1891, were the pioneers of weather forecasting in the United States. Gen. Greely, in his work on American Weather, has put on record a number of precepts deduced from his own experience and observation. With this exception, but little has been preserved in printed form of the rules which obtained during the early period. Nevertheless, many of the formulas and precepts of the older art have been communicated orally from the master to the pupil and as thus handed down are now doubtless incorporated in transmuted form in the accompanying work.

ALFRED J. HENRY,
Chairman.

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CONTENTS.

		Page.
Chapter I.	Introductory note—General principles and theories of atmospheric motions	15
II.	General circulation of the atmosphere	33
III.	Weather forecasting—Preliminary statement of the problem	69
IV.	Auxiliary pressure change charts	77
V.	Highs and Lows—General considerations	93
VI.	Cold waves	143
VII.	Frosts	177
VIII.	High winds	217
IX.	Fog, snow, sleet, and thunderstorms	253
X.	Weather and temperature forecasts—Washington district	279
XI.	Weather and temperature forecasts—Chicago district	293
XII.	Weather and temperature forecasts—New Orleans, Denver, Portland, and San Francisco districts	317
XIII.	Long-range forecasts and bibliography	341

LIST OF ILLUSTRATIONS.

Frontispiece—Forecast districts.

Chapter I.

Fig. No.		
1.	Illustrating the forces which cause and modify the winds	22
2.	Cyclonic circulation, first stage	28
3.	Cyclonic circulation, second stage	28
4.	Cyclonic circulation, third stage	29
5.	Cyclonic circulation, fourth, or equilibrium stage, for nearly frictionless flow	29
6.	Anticyclonic circulation	31

Chapter II.

7.	Annual, summer, and winter, wind velocities with altitude	37
8.	Winter, and summer, vertical temperature gradients	38
9.	Temperature distribution with altitude, Northern Hemisphere	40
10.	Pressure distribution with altitude, Northern Hemisphere	40
11.	Prevailing direction of monsoon winds, Northern Hemisphere	43
12.	Prevailing direction of monsoon winds, Southern Hemisphere	44
13.	Average annual isobars	61
14.	Ocean winds, January and February	62
15.	Ocean winds, July and August	63

Digitized by Google

CHAPTER III.

Page.
16. Weather map of March 2, 1904 72
17. Weather map of March 3, 1904 72
18. Pressure and temperature changes, March 2, 1904 72
19. Pressure and temperature changes, March 3, 1904 72
20. Pressure distribution of June 14, 1900, illustrating the saddle formation 76

CHAPTER IV.

21. Idealized barograph curve, illustrating inconsistencies in the ratio of the 12 to the 24 hour changes 80
22. Katallobars, November 12–15, 1911 83
23. Katallobars, November 15–18, 1911 83
24. Lows and attendant katallobars, November 12–18, 1911 83
25. Various lows and katallobars, illustrating division of katallobars, January 9, 1903 83
26. Additional lows, January 6, 1898, and others 85
27. High of January 22, 1905, and the several anallobars that attended it 85
28. A single high, January 10, 1903, and a single low (in the rear), in two colors .. 85
29. Stagnant highs and allobaric phenomenon 85
30. Average number of hours anallobars precede highs 89

CHAPTER V.

31. Average paths of lows, January 95
32. Average paths of lows, July 95
33. Path of slow-moving low of April 4, 1895 105
34. Path of erratic low of February 8–9, 1894 106
35. Isobars and pressure change chart (12-hour), 8 a. m. February 8, 1894 106
36. Isobars and pressure change chart (12-hour), 8 p. m. February 8, 1894 106
37. Isobars and pressure change chart (12-hour), 8 a. m. February 9, 1894 106
38 Slow-moving *Low* of April 18, 1910 (isobars in black; isotherms and path of low in red) 121
39. Barograph trace, Roseburg, Oreg., January 23–26, 1914 116
40. Paths of North Pacific lows, May, 1905–1909 118
41. Paths of North Pacific lows, January, 1900–1909 (two colors) 121
42. Paths of Alberta lows, January, 1900–1909 (two colors) 121
43. Types of southwest lows, No. 1, November 12, 1909 123
44. Types of southwest lows, No. 2, November 15, 1909 123
45. Types of southwest lows, No. 3, November 19, 1907 123
46. Types of southwest lows, No. 4, November 15, 1910 123
47. Types of southwest lows, No. 5, November 7, 1911 125
48. Types of southwest lows, No. 6, November 17, 1907 125
49. Rapid movement of high of December 19, 1914 (isobars and path of high in black; isotherms in red) 130
50. Rapid movement of high of November 18, 1914 (isobars and path of high in black; isotherms in red) 130
51. Reenforced high of February 8, 1906 (isobars in black; isotherms in red) ... 131
52. Reenforced high of February 9, 1906 (isobars in black; isotherms in red) ... 131
53. Reenforced high of February 10, 1906 (isobars in black; isotherms in red) .. 131
54. Temperature changes in a high, winter, February 4, 1906 136
55. Temperature changes in a high, winter, February 5, 1906 136
56. Temperature changes in a high, winter, February 6, 1906 136
57. Temperature changes in a high, winter, February 7, 1906 136

Digitized by Google

Page.
58. Temperature changes in a high, summer, July 15, 1896..... 136
59. Temperature changes in a high, summer, July 16, 1896..... 136
60. Temperature changes in a high, summer, July 17, 1896..... 136
61. Temperature changes in a high, summer, July 18, 1896..... 136

CHAPTER VI.

62. Verifying temperature fall and cold wave temperature limit, March to November, inclusive..... 144
63. Verifying temperature fall and cold wave temperature limit, December, January, and February..... 144
64. Absolute minimum temperatures, 1871–1913..... 146
65. Normal 8 a. m. temperatures in January (third decade)..... 147
66. Number of cold waves, 1904–1914, inclusive..... 148
67. Cold wave types, November 10, 1911 (isobars in black; isotherms in red). 156
68. Cold wave types, November 11, 1911 (isobars in black; isotherms in red). 156
69. Cold wave types, March 5, 1913 (isobars in black; isotherms in red)..... 156
70. Cold wave types, March 6, 1913 (isobars in black; isotherms in red)..... 156
71. Cold wave types, February 3, 1906 (isobars in black; isotherms in red)... 158
72. Cold wave types, February 4, 1906 (isobars in black; isotherms in red)... 158
73. Cold wave types, January 12, 1907 (isobars in black; isotherms in red)... 158
74. Cold wave types, January 13, 1907 (isobars in black; isotherms in red)... 158
75. Cold wave types, December 5, 1909 (isobars in black; isotherms in red).. 158
76. Cold wave types, December 6, 1909 (isobars in black; isotherms in red).. 158
77. Cold wave types, January 4, 1913 (isobars in black; isotherms in red).... 158
78. Cold wave types, January 5, 1913 (isobars in black; isotherms in red).... 158
79. Cold wave types, January 6, 1913 (isobars in black; isotherms in red).... 158
80. Cold wave types, January 7, 1913 (isobars in black; isotherms in red).... 158
81. Cold wave types, January 8, 1913 (isobars in black; isotherms in red).... 159
82. Cold wave types, December 18, 1908 (isobars in black; isotherms in red). 159
83. Cold wave types, December 19, 1908 (isobars in black; isotherms in red). 159
84. Cold wave types, January 13, 1914 (isobars in black; isotherms in red)... 160
85. Cold wave types, January 14, 1914 (isobars in black; isotherms in red)... 160
86. Cold wave types, November 12, 1908 (isobars in black; isotherms in red). 160
87. Cold wave types, November 13, 1908 (isobars in black; isotherms in red). 160
88. Cold wave types, November 14, 1908 (isobars in black; isotherms in red). 160
89. Cold wave types, February 8, 1909 (isobars in black; isotherms in red)... 160
90. Cold wave types, February 9, 1909 (isobars in black; isotherms in red)... 160
91. Cold wave types, February 3, 1913 (isobars in black; isotherms in red)... 162
92. Cold wave types, February 4, 1913 (isobars in black; isotherms in red)... 162
93. Cold wave types, February 5, 1913 (isobars in black; isotherms in red)... 162
94. Cold wave types, February 6, 1913 (isobars in black; isotherms in red)... 162
95. Cold wave types, March 1, 1913 (isobars in black; isotherms in red)..... 162
96. Cold wave types, March 2, 1913 (isobars in black; isotherms in red)..... 162

CHAPTER VII.

97. The average date of the last killing frost in spring [1]..... 181
98. The latest date on which a killing frost occurred in spring [1]..... 182
99. The average date of the first killing frost in autumn [1]..... 183
100. The earliest date on which killing frost has occurred in autumn [1]..... 184
101. Weather map, August 7, 1904; summer frost in Wisconsin ("frost type maps"; isobars in black; isotherms in red)..... 187

[1] From Weather Bureau Bulletin V, Frost Data of the United States.

Digitized by Google

Page.

102. Weather map, August 8, 1904; summer frost in Wisconsin ("frost type maps"; isobars in black; isotherms in red)..... 186
103. Weather map, April 10, p. m., 1911; spring frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 188
104. Weather map, April 11, p. m., 1911; spring frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 188
105. Weather map, April 12, p. m., 1911; spring frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 188
106. Weather map, April 13, p. m., 1911; spring frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 188
107. Weather map, September 23, 1908; autumn frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 189
108. Weather map, September 24, 1908; autumn frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 189
109. Weather map, September 25, 1908; autumn frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 189
110. Weather map, September 26, 1908; autumn frost in Washington and Oregon ("frost type maps"; isobars in black; isotherms in red)..... 189
([1]) Weather map, January 5, 1913; freezing temperature in southern California ("frost type maps"; isobars in black; isotherms in red).
Weather map, January 6, 1913; freezing temperature in southern California ("frost type maps"; isobars in black; isotherms in red).
Weather map, January 7, 1913; freezing temperature in southern California ("frost type maps"; isobars in black; isotherms in red).
Weather map, January 8, 1913; freezing temperature in southern California ("frost type maps"; isobars in black; isotherms in red).
111. Weather map, November 26, 1903; autumn frost in Florida ("frost type maps"; isobars in black; isotherms in red)..... 190
112. Weather map, November 27, 1903; autumn frost in Florida ("frost type maps"; isobars in black; isotherms in red)..... 190
113. Weather map, November 28, 1903; autumn frost in Florida ("frost type maps"; isobars in black; isotherms in red)..... 190
114. Weather map, February 12, 1899; winter freeze in Florida ("frost type maps"; isobars in black; isotherms in red)..... 191
115. Weather map, February 13, 1899; winter freeze in Florida ("frost type maps"; isobars in black; isotherms in red)..... 191
116. Weather map, February 14, 1899; winter freeze in Florida ("frost type maps"; isobars in black; isotherms in red)..... 191
117. Weather map, May 10, 1907; spring frost type, lake region ("frost type maps"; isobars in black; isotherms in red)..... 193
118. Weather map, May 11, 1907; spring frost type, lake region ("frost type maps"; isobars in black; isotherms in red)..... 193
119. Weather map, May 12, 1907; spring frost type, lake region ("frost type maps"; isobars in black; isotherms in red)..... 193
120. Weather map, September 13, 1911; autumn frosts in New England..... 194
121. Weather map, September 14, 1911; autumn frosts in New England..... 194
122. Weather map, September 15, 1911; autumn frosts in New England..... 194
123. Weather map, May 16, 1910; spring frost in Rocky Mountain region..... 194
124. Weather map, May 17, 1910; spring frost in Rocky Mountain region..... 194

[1] See Figs. 78–81.

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CHAPTER VIII.

Illustrating low in central valleys between two highs: Page.

125. Weather map, November 25, 1895–a (isobars in black; isotherms in red).. 223
126. Weather map, November 25, 1895–p (isobars in black; isotherms in red).. 223
127. Weather map, December 26, 1904–p (isobars in black; isotherms in red).. 223
128. Weather map, December 27, 1904–a (isobars in black; isotherms in red).. 223

Illustrating development of low south of high:

129. Weather map, November 12, 1904–a (isobars in black; isotherms in red).. 223
130. Weather map, November 12, 1904–p (isobars in black; isotherms in red).. 223
131. Weather map, November 13, 1904–a (isobars in black; isotherms in red).. 223
132. Weather map, November 27, 1912–a (isobars in black; isotherms in red).. 223
133. Weather map, November 27, 1912–p (isobars in black; isotherms in red).. 223

Illustrating development of low in southern end of trough:

134. Weather map, February 28, 1914–a (isobars in black; isotherms in red).. 224
135. Weather map, February 28, 1914–p (isobars in black; isotherms in red).. 224
136. Weather map, March 1, 1914–a (isobars in black; isotherms in red)..... 224
137. Weather map, March 1, 1914–p (isobars in black; isotherms in red)..... 224
138. Pressure changes (4-hour) 8 a. m. to 12 noon, February 28, 1914..... 225
139. Pressure changes (4-hour) 12 noon to 4 p. m., February 28, 1914..... 225
140. Pressure changes (4-hour) 4 p. m. to 8 p. m., February 28, 1914 226
141. Pressure changes (4-hour) 8 p. m. to midnight, March 1, 1914 226
142. Pressure changes (4-hour) midnight to 4 a. m., March 1, 1914..... 227
143. Pressure changes (4-hour) 4 a. m. to 8 a. m., March 1, 1914..... 227
144. Pressure changes (4-hour) 8 a. m. to noon, March 1, 1914 228
145. Pressure changes (4-hour) noon to 4 p. m., March 1, 1914 228
146. Pressure changes (4-hour) 4 p. m. to 8 p. m., March 1, 1914..... 229

Further examples of southern development:

147. Weather map, February 8, 1903–a (isobars in black; isotherms in red)... 229
148. Weather map, February 8, 1903–p (isobars in black; isotherms in red)... 229
149. Weather map, December 17, 1904–p (isobars in black; isotherms in red).. 229
150. Weather map, December 18, 1904–a (isobars in black; isotherms in red).. 229

Folder, West Indian hurricane maps:

151. Weather map, August 17, 1886–a (isobars in black; isotherms in red).... 232
152. Weather map, August 18, 1886–a (isobars in black; isotherms in red)..... 232
153. Weather map, August 19, 1886–a (isobars in black; isotherms in red)..... 232
154. Weather map, August 20, 1886–a (isobars in black; isotherms in red)..... 232
155. Weather map, August 26, 1893–p (isobars in black; isotherms in red).... 232
156. Weather map, August 27, 1893–p..... 232
157. Weather map, August 28, 1893–p (isobars in black; isotherms in red).... 232
158. Weather map, August 29, 1993–p (isobars in black; isotherms in red).... 232

Illustrating the movement of lows inland over the North Pacific coast:

159. Weather map, November 28, 1913–a (isobars in black; isotherms in red).. 245
160. Weather map, November 28, 1913–p (isobars in black; isotherms in red).. 245
161. Weather map, November 29, 1913–a (isobars in black; isotherms in red).. 245
162. Weather map, November 29, 1913–p (isobars in black; isotherms in red).. 245

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CHAPTER IX.

Page.

163. Heavy snow type, southern New England, December 22, 1908—shaded area indicates region of snow (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 255
164. Snow type (western low), February 14, 1910 (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 255
165. Snow type (western low), February 15, 1910 (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 255
166. Snow type (western low), February 16, 1910 (interior valleys) (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 255
167. Annual frequency of sleet storms..... 256
168. Sleet type, interior valleys (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 257
169. Sleet type, Middle Atlantic States, January 28, 1912 (isobars in black; letters in red; S—snow; Sl—sleet: F—fog)..... 257
170. Sleet type, Middle Atlantic States, January 29, 1912 (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 257
171. Text figure, fog frequency in days, Atlantic coast..... 265
172. Weather map, January 18, 1900; fog types (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 268
173. Weather map, January 19, 1900; fog types (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 268
174. Text figure, fog frequency in days, Gulf coast..... 270
175. Weather map, January 22, 1908; fog types (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 274
176. Weather map, February 9, 1898; fog types (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 274
177. Weather map, February 10, 1898; fog types (isobars in black; letters in red; S—snow; Sl—sleet; F—fog)..... 274
178. Thunderstorm type, low NW., high SE., June 10, 1898–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 276
179. Thunderstorm type, low NW., high SE., June 11, 1898–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 276
180. Thunderstorm type, low NW., high SE., June 12, 1898–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 276
181. Thunderstorm type, low NW., high SE., June 13, 1898–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 276
182. Thunderstorm type, Atlantic high, projecting westward, August 10, 1905–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 277
183. Thunderstorm type, Atlantic high, projecting westward, August 11, 1905–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 277
184. Thunderstorm type, Atlantic high, projecting westward, August 12, 1905–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 277
185. Thunderstorm type, Atlantic high, projecting westward, August 13, 1905–p. (isobars in black; isotherms and thunderstorms symbols in red)..... 277

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CHAPTER XII.

Page.
186. Isobars and isotherms, North Pacific, January..... 327
187. Isobars and isotherms, North Pacific, July..... 327
Figures 188–199. General title, weather maps illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation.
Illustrating movement of California low:
188. Weather map, p. m., July 7, 1913, illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation..... 324
189. Weather map, a. m., July 8, 1913, illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation..... 324
190. Weather map, p. m., July 8, 1913, illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation..... 324
191. Weather map, a. m., July 9, 1913, illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation..... 324
192. Weather map, p. m., July 9, 1913, illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation..... 324
193. Weather map, a. m., July 10, 1913, illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation..... 324
194. Weather map, a. m., July 11, 1913, illustrating the movement of highs and lows; Pacific coast; isobars in black; isotherms in red; shaded areas——24-hour precipitation..... 324
195. Weather map, September 2, 1913, illustrating movement of first low of season from North Pacific..... 329
196. Weather map, September 3, 1913, illustrating movement of first low of season from North Pacific..... 330
197. Weather map, January 23, 1913, illustrating winter chinook..... 333
198. Weather map, January 24, 1913, illustrating winter chinook..... 333
199. Weather map, July 17, 1912, illustrating summer chinook..... 334

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WEATHER FORECASTING IN THE UNITED STATES.

CHAPTER I.

INTRODUCTORY NOTE.

By Prof. C. F. MARVIN.

General principles and theory of atmospheric motions 15
Numerical data and results 22
The weather map 25
Cyclonic and anticyclonic circulations 25

GENERAL PRINCIPLES AND THEORY OF ATMOSPHERIC MOTIONS.

Atmospheric circulation, whether manifesting itself, for example, in a monsoon or in a gentle lake breeze, is a gravitational phenomenon induced and maintained by temperature differences. If there were no differences whatsoever in temperature throughout its different parts, the atmosphere of the earth would quickly settle into a state of rest relative to the surface of the earth. What is called the circulation—that is, the winds—would cease. The distribution of atmospheric pressure would then be that demanded by gravity on a rotating globe. In the study of the motions of the atmosphere, we must not forget that the earth is a rotating globe. The differences of temperature in different portions of the atmosphere, however, are sometimes very great, and great motions, or winds, are caused thereby. This is illustrated by the flow of water between two adjacent tanks connected by an upper and a lower pipe and kept at different temperatures. Similarly, in the case of the atmosphere, if two adjacent columns of air, or the masses of air over two adjoining regions, whether of large area or small, are kept at different temperatures there will occur, through the action of gravity, a continuous overflow from the warmer to the colder and an underflow from the colder to the warmer, unless prevented by some extraneous influence.

In addition to these universal or ultimate causes of circulation there also are modifying factors—friction, viscosity, turbulence, local heating, local cooling, deflection by mountains, deflection due to the

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earth's rotation, and others—which make one atmospheric movement different from another in extent, duration, direction, and velocity.

Since the atmosphere is a fluid of which the viscosity, though small, is definitely known, it might seem that by means of the equations of thermodynamics and hydrodynamics one could as certainly foretell its every movement and future conditions as one can predict an eclipse or an occulation from the equations of celestial mechanics. But for many reasons this is far from true. Thus, the irregularity of surface heating and the action of mountains in deflecting winds, both horizontally and vertically, complicate the problem so as to make an exact solution impossible. Moreover, there are changes in the amount of atmosphere involved. Matter in the form of water vapor is added in large amounts by evaporation to the volume of circulating gases, while at an equal average rate, but not simultaneously, it is withdrawn by precipitation, chiefly in the regions of LOWS.[1]

Though the wind at an altitude of several hundred meters, or more, is comparatively steady, except in very rough or mountainous regions, near the surface of the earth it is always in a turmoil, because of surface friction which checks the lower air while the layers above tumble forward and down, and because of numerous objects which obstruct the course and introduce cross currents. Places near the surface of the earth and no more than 50 feet apart, though having the same average wind direction and velocity, commonly have different, often very different, winds. These differences of speed and direction are of great significance in connection with the wracking effects of winds on houses, bridges, and other structures, especially when the fluctuations have a periodicity synchronous with that of the structure or its parts. They are also of much importance to the aviator, not only upon starting and landing, but also during flight.

However valuable an exact knowledge of surface air movements would be, it is obvious that these movements defy all attempts at mathematical formulation. Nevertheless, the average effect of a group of turbulent wind eddies is amenable to mathematical discussion.[2] Furthermore, while an exact mathematical solution of the problem of world-wide circulation is not now possible, many features of this circulation and the forces and influences which modify winds are nevertheless clearly comprehensible from physical considerations, and admit of at least approximate mathematical representation. Some of these features characterize equally all the more general winds, and it seems appropriate to discuss them independ-

[1] Signifies areas over which atmospheric pressure is low.
[2] Taylor, Phil. Trans. Roy. Soc. A., 215, pp. 1–26, 1915.

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ently in a common introduction to the more detailed accounts of certain types of atmospheric circulation which will follow.

Forces and influences that modify winds.—All winds that travel a considerable distance acquire characteristics of direction and speed, more or less dependent upon the rotation of the earth. They are continually acted upon by deflective forces that ultimately greatly influence the direction, and to some extent the velocity of motion.

Change of velocity with change of latitude.—When, because of the great temperature contrasts between equatorial and polar regions, air moves from lower to higher latitudes, its velocity with reference to the surface of the earth must change. It might seem, as many have assumed, that the absolute velocity of the air would tend to remain constant, and, therefore, to blow from west to east as soon as it had crossed that latitude on which the velocity of the ground is the same as the original absolute west-to-east velocity of the mass of air in question. This assumption, however, is theoretically incorrect, as has often been explained. A particle of the atmosphere, or any portion of it moving as a unit, in reality is rotating around the axis of the earth. Hence, in considering latitude effect or effect of distance from the earth's axis on wind velocity, it is necessary to remember that the angular momentum, $mr^2\omega$ (in which m is the mass, r its distance from the axis of rotation, and ω the angular velocity), is a constant. In other words, the law of conservation of areas applies, and if a given mass of atmosphere, m, moves to a higher latitude, r becomes smaller and the velocity of the mass, by the law of equal areas, can not remain the same, as is often supposed, but rather should tend to become greater in proportion to the secant of the latitude. If the air moves to lower latitudes, its velocity obviously tends to diminish.

As a matter of fact no such enormous changes of velocities of the atmosphere with change of latitude as the principle of the conservation of areas would demand in the higher latitudes are ever found either at the surface or at other levels. This, however, does not invalidate the principle itself, but only shows that there are very effective damping or retarding influences in operation.

Viscosity, or the friction between two layers of air gliding over each other, is one of these retarding influences, but its effect is probably very small. A larger effect involving only the lower strata comes from surface friction and turbulence induced by trees, hills, and other irregularities, which operate powerfully to stop or retard any relative motion of the air over the earth. Finally, vertical convection is a still greater velocity control, greater, probably, than all others in the magnitude of its effects. Convection leads to extensive interchange of momentum between lower and upper layers of the

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atmosphere and thus transfers the retarding effects of surface friction to higher strata, tending to bring the atmosphere at all levels to a common velocity. Surface friction and viscosity tend to cause the air to revolve with the earth, all as a rigid mass. Convection, however, operates to prevent this and tends to suppress differences of velocity in different vertical strata. Because of these several influences the actual velocity at all levels and especially at high latitudes differs from that which the law of equal areas would lead us to expect.

Deflective force due to earth's rotation.—The deflective influence of the earth's rotation on the direction of motions of winds, ocean currents, and in fact on any objects moving freely over the earth's surface, is of great importance and has many far-reaching effects. Many expositions of this dynamic problem are to be found in standard works on meteorology, mechanics, and physics, which the student must consult for the full details. The essential facts may be briefly stated as follows:

Any objects whatsoever moving over the surface of the earth are subjected to a more or less pronounced deflective influence that tends to cause the body to swerve to the right of its onward course in the Northern, and to the left in the Southern Hemisphere. The magnitude of this deflective influence is

$$f_1 = 2mV\ \omega \sin \phi \qquad (1)$$

in which m is the mass of the moving body, V its horizontal velocity, ω the angular velocity of rotation of the earth on its axis, and ϕ the latitude of the place in question.

From equation (1) and related considerations it follows that the deflective force due to the rotation of the earth on any object moving horizontally is:

a. Directly proportional to the mass of the body, m.
b. Directly proportional to the horizontal velocity, V.
c. Directly proportional to the angular velocity of the earth's rotation, ω,=a constant.
d. Directly proportional to the sine of the latitude, ϕ, of the moving object.
e. Of the same value whatever the horizontal direction of motion.
f. Always at right angles to the instantaneous direction of motion and, therefore, wholly without influence on the speed of the body.
g. The force deflects moving bodies always to the right of their onward course in the Northern Hemisphere and to the left in the Southern Hemisphere.

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Since the deflective influence is at all times at right angles to the path, it follows that an object once set moving freely and in a frictionless manner over the surface of the earth would describe a continuously curved path.

Centrifugal effects.—Whenever bodies move in curved paths a deflective force is always acting perpendicularly to the path and directly toward the center of curvature. If it were not for such a radial or centripetal force the body would move in a straight line. Such a moving body always displays a *tendency to fly away from the center*, and while this tendency is frequently designated centrifugal force, nevertheless, in the ordinary meaning of the word force no true force acting *away* from the center of curvature exists. but rather an inwardly acting radial force is required to deflect the body constantly from the straight line it is momentarily following. The value of this force is given by the well-known equation,

$$F = \frac{mV^2}{r} \tag{2}$$

in which m equals mass, V equals linear velocity, and r equals radius of curvature of the path at the point occupied by the body. Since the earth's deflective influence f_1 (eq. 1) causes a body moving freely in a horizontal surface to describe a curved path and since a body moving in a curved path must be acted upon by a centripetal force, F (eq. 2) therefore, when no other deflective forces are in operation

$$f_1 = F, \text{ hence, } \frac{mV^2}{r_0} = 2mV\omega \sin \phi$$

$$\text{or } r_0 = \frac{V}{2\omega \sin \phi} \tag{3}$$

in which r_0 is the radius of curvature of the path *when the earth's rotative effect is the only deflecting force.*

It would be interesting to trace the path of a body moving freely and in a frictionless manner over a rotating sphere like the earth to which the body is held by gravitation. So far as indicating atmospheric motions is concerned, however, such a study would serve but little purpose, because to neglect the effects of viscosity, turbulence, surface friction, convection, temperature, and other influences leads to results entirely at variance with those commonly observed. We see from equation (3), however, that the smaller the linear velocity of the moving object over the surface of the earth or the greater the latitude the smaller will be the radius—that is, the greater the rate of curvature. On the Equator the radius of curvature is infinite, or the path a straight line. However, unless the object is moving along the Equator it soon gets to one side, where the curvature again becomes finite. On crossing the Equator the

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direction of curvature changes, as is well shown by the summer wind tracks over the Indian Ocean.

Other deflective forces.—Whenever the path of a body moving on the earth has a greater or less curvature than that required by equation (3) or when the direction of curvature is reversed it is clearly apparent that the body is acted upon by some other deflective influence than that due to the earth's rotation. If f_2 represents the resultant of all other deflective forces in action, then the actual curvature of the path will be wholly determined by the two forces f_1 and f_2, and the following equation must apply:

$$F=\frac{mV^2}{r}=f_1+f_2=2m\omega V\sin\phi+f_2$$

$$f_2=\frac{mV^2}{r}-2m\omega V\sin\phi \qquad (4)$$

The term $F=\frac{mV^2}{r}$ is the measure of the deflective or centripetal force necessary to give the path its actual radius of curvature r. This force may be regarded as positive for right-handed deflection, that is, for clockwise gyration, and negative for the reverse direction of motion. It is highly important that the student clearly understands how the algebraic signs of the terms in equation (4) are fixed and the significance thereof. For right-hand rotation, r is regarded as positive. Its values become infinite for straight-line motion and must be taken as negative for deflection to the left or counter-clockwise. The last term of the second member, that is, $f_1=2m\omega V\sin\phi$, causes right-hand motion in the northern hemisphere and is therefore positive, but f_1 is negative in the southern hemisphere. The sign before this term simply shows that the difference of the forces must be taken. The sign for f_2 is fixed when those of the second member of the equation are determined. The force f_2, however, although representing "other deflective forces" in the equation, nevertheless depends chiefly or wholly upon the gravitational pressure gradient and whenever the pressure gradient or component thereof acts to produce right-handed deflection of onward moving air, f_2 must be considered as positive, and vice versa.

Gravitational pressure gradient.—Gravity is the immediate or direct cause of practically all important atmospheric motions, and the term gravitational pressure gradient, or, more briefly, pressure gradient, therefore deserves to be carefully defined. A form of statement appropriate to present requirements is somewhat as follows: The pressure gradient at a given place is the difference in barometric pressure at the ends of a line of small length taken horizontally and at right angles to the direction of the isobars cutting the line, divided by the length of the line. The effect of gravity in causing

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the air to move in the direction perpendicular to the isobars is proportional to this pressure gradient. The force in symbols may be stated as follows:

$$f = \frac{m dp}{\rho dn}, \tag{5}$$

in which ρ=density of the air, dp the small difference in pressure in the short distance dn.

The action of gravity through the agency of the pressure gradient is the force that actually sets atmospheric air in motion and this force, or at least components of it, constitutes the additional deflective force designated f_2 in the foregoing equations. Let us assume, for the sake of further analysis, that all frictional and opposing resistances are absent, and that the whole effect of the pressure gradient is expended in deflecting the moving air; that is, in compelling it to maintain its curvilinear path. We must then write,

$$\frac{dp}{\rho dn} = \frac{V^2}{r} - 2\omega V \sin \phi \tag{6}$$

which is an equation for the frictionless motion of air masses around a region of low pressure when all resistances are absent and the motion has become perfectly steady under the pressure gradient $\frac{dp}{dn}$.

Gradient velocity.—When gyrating masses of air have attained sensibly continuous steady motion under the conditions defined in the foregoing and represented by equation (6), a state of dynamic equilibrium exists. The value of V, that satisfies equation (6), is then called the *gradient velocity*. In nature the gradient velocity can not be attained at the surface because of friction and other obstructions. The velocity may be approximately reached, however, at elevations of a kilometer or more, and, if fully attained, the direction of motion is necessarily *parallel to the isobars*.

Automatic adjustment of winds in direction and velocity.—Generally the path of the wind is *inclined* to, not *parallel* with the isobars. In this case the gradient force will have two components of effect on the moving air, one normal, the other tangent to the path. The *normal* component constitutes the deflective force f_2 of equation 4, and tends to change the direction of the motion. The *tangential* component increases or diminishes the velocity of the wind, according as that velocity is less or greater than the gradient velocity. Whenever the wind arrows, showing motions of a gyratory system, cross the isobars *in the direction* of the pressure gradient, the tangential component of force then acts *with* the motion and tends to increase the velocity so that the gradient velocity should be attained, but friction and other resistances prevent. On the other hand, when the wind arrows cross the isobars in a direction *opposed* to the

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pressure gradient the tangential component of the force will then check the motion. Such a condition signifies that the actual velocity is already greater than the gradient velocity. The forces are graphically indicated for certain representative cases in figure 1.

From the foregoing simple considerations it appears that the forces governing the motions of relatively free-air masses in a cyclonic system tend automatically to establish and maintain a condition of equilibrium in which the velocity of motion is practically the gradient velocity, and the direction of motion then becomes parallel with the isobars.

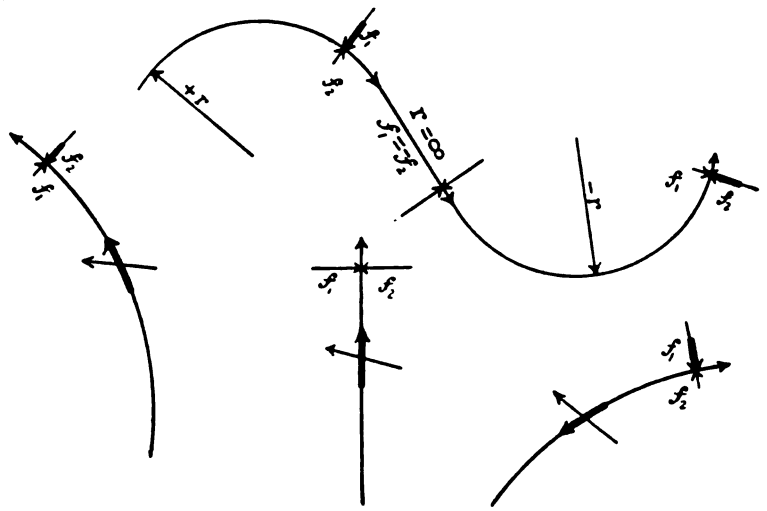

FIG. 1.—*Scheme to depict forces causing and modifying winds.*—Pressure gradient is indicated by short arrows crossing line of motion near the middle. Heavy body portion of line indicates component of gradient tending to overcome resistance, or increase or retard velocity. f_1 and f_2 are deflective forces due to earth and gradient, respectively. Heavy portion of one of these forces is dominating component, and remainder of same force equals and neutralizes the force on the opposite side. Centrifugal forces, in the ordinary meaning of the word, have no existence in any of the instances illustrated. Sometimes f_1 sometimes f_2 acts from the center outwardly. These may then properly be called centrifugal forces, but they are entirely different in origin and magnitude from the inertia reaction commonly designated centrifugal force.

Although equation (6) applies strictly only to certain ideal conditions, nevertheless it must be recognized that other cases are also represented, in which the force f_2 comprises, not the whole pressure gradient effect, but only a component thereof. The velocity will then not be the true gradient velocity and the wind direction will cross the isobars.

NUMERICAL DATA AND RESULTS.

The computation of a few numerical results by the aid of the equations deduced in the foregoing will illustrate their use and show the relative magnitudes of some of the forces and elements represented.

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The value of the gradient velocity, V from equation (6) is readily found to be:

$$V=\sqrt{\frac{rdp}{\rho dn}+(\omega r\sin\phi)^2}+\omega r\sin\phi$$

For cyclonic circulation in the Northern Hemisphere the sign before the last term becomes negative, because the motion is counter-clockwise and r is negative. The term $\frac{rdp}{dn}$ will generally be positive, because both factors are positive or negative together. If the path of the wind is straight the deflective force from the earth's rotation is just neutralized by the effect of pressure gradient. In the Northern Hemisphere this can occur only when the pressure decreases to the leftward of the line of motion. In this case the radius of curvature of the path is infinite and we get from equation (6),

$$V=\frac{1}{2\omega\rho\sin\phi}\left(\frac{-dp}{dn}\right). \qquad (8)$$

The minus sign signifies that the pressure gradient acts to the left.

In the C. G. S. system of units:

V=Centimeters per second.

$\frac{dp}{dn}$=Difference in dynes pressure per square centimeter, per centimeter horizontal distance at right angles to isobar.

r=Radius of curvature, in centimeters, of wind path at place of observation, *not distance to center of low.*

ρ=Grams of air per cubic centimeter.

ω=Angle through which the earth turns per second=$\frac{2\pi}{86{,}164}$.

Sin ϕ=Natural sine of the angle of latitude. Let the latitude be 40°, the radius of curvature 500 kilometers, the density of air .0011, a value it may often have 1 kilometer above sea level, and the pressure gradient such as to give a barometric difference of 1mm. per 50 kilometers.

With these values V=18.55 meters per second=41.5 miles per hour.

If, under the above conditions of latitude, density and pressure gradient, the wind is given a higher velocity, the value of f, due to the earth's rotation, increases and the path becomes less curved. For a straight path the velocity by equation (8) must be,

V=25.89 meters per second=57.9 miles per hour.

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TABLE 1.—*Data relative to atmospheric motions.*

SECTION I.—CENTRIFUGAL FORCE IN DYNES FOR MASS OF 1 GRAM.

Radius miles.	Velocity miles per hour.				
	200	100	75	50	25
400	1.242	0.310	0.175	0.078	0.019
200	2.483	.621	.349	.155	.039
100	4.966	1.242	.689	.310	.078
50	9.933	2.483	1.398	.621	.155
25	19.867	4.966	2.795	1.242	.310

SECTION II.—DEFLECTIVE FORCE OF EARTH'S ROTATION ON MASS OF 1 GRAM.

Lat. ϕ	Velocity in miles per hour.					r_0 miles. V=100 miles per hour.
	200	100	75	50	25	
20	0.446	0.223	0.167	0.112	0.055	557
30	.652	.326	.244	.163	.082	381
40	.838	.419	.314	.210	.105	296
50	.989	.494	.371	.247	.124	249
60	1.129	.564	.423	.282	.141	220
70	1.225	.612	.460	.306	.153	203
80	1.284	.642	.482	.321	.160	193

SECTION III.—PRESSURE GRADIENT IN DYNES, WHEN ISOBARS FOR EACH 1/10 INCH ARE AT DIFFERENT DISTANCES APART, STATUTE MILES; ρ=0.0012.

200	100	75	50	25
0.0677	0.1754	0.2630	0.3507	0.7015

Equations.—Forces are expressed in dynes for mass of 1 gram, velocities in statute miles per hour, lengths and distances in statute miles.

Centrifugal force, $F=0.012418\frac{V^2}{r}$.

Earth's deflective influence at latitude ϕ $f=.005620\ V \sin \phi$.

When the deflective influence due to the earth's rotation is the only deflecting force acting, the radius of curvature in the case of horizontal motion at latitude ϕ will be:

$$r_0=1.9047\frac{V}{\sin \phi}.$$

Pressure gradient.—A barometric pressure difference of one-tenth of an inch corresponds to a force of 3,387 dynes. An average value of ρ, the density of the air near the surface of the earth is ρ=0.0012 grams per cubic centimeter. With these data the pressure gradient is

$$\frac{dp}{\rho dn}=\frac{17.539}{s}.$$

in which s is the distance in statute miles between isobars at intervals of one-tenth of an inch of pressure.

The relative values of the centripetal force, the earth's deflective force, and that due to gradient are clearly shown in the table for

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certain representative values of wind velocity from 25 to 200 miles per hour and different latitudes and radii of curvature and for different spacings between isobars of from 25 to 200 miles.

The values of the forces are given in dynes. The magnitude of this unit of force is clearly grasped by remembering that the attraction of gravity on 1 gram is approximately 981 dynes. For example, the earth's deflective force at latitude 50° and velocity 200 miles per hour is 0.989 dynes on a mass of 1 gram—that is, the gross deflective force on a mass moving at 200 miles per hour at latitude 50° is one-thousandth part of its weight. Obviously, the other magnitudes are in proportion.

The centripetal force in the case of motions at high velocities and short radii of curvature are plainly much greater than the other forces, and motions of that character are possible only under great pressure gradients. For example, in north latitude 40°, air moving counter-clockwise at 200 miles per hour in a circle of radius 25 miles requires a pressure gradient greater than

$$19.867+0.838=20.705 \text{ dynes},$$

or more intense than one-tenth inch per mile.

The last column of Section II of the table gives the radius of curvature of the wind paths for different latitudes and at a velocity of 100 miles per hour when the earth's rotative effect is the only deflective force. For other velocities the radii are directly proportional. The relative smallness of the earth's deflective force is quite apparent as also its considerable increase at higher latitudes.

THE WEATHER MAP AND NOTES ON THE CIRCULATION IN CYCLONES AND ANTICYCLONES.

The weather map.—This indispensable adjunct in studies of atmospherics is so well known that not even a brief description is here necessary. It is important, however, not to be misled by the somewhat conventional way in which certain atmospheric conditions are depicted on weather maps. When a system of isobaric lines has been drawn we get a picture of the pressure distribution over the region represented. The universal, in fact the necessary, practice is to single out and mark certain particular regions LOW[1], HIGH[1], etc. If the map is "flat," as the expression goes, there may be several such LOWS and HIGHS. If we had sufficient data and drew isobars for hundredths instead of tenths of inches, the "flat" map would probably show relative lows and highs in still greater number. On other occasions, however, the configurations of the isobars

[1] Signifies areas of low pressure and areas of high pressure, respectively.

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bring out in great distinctness great systems of cyclonic and anticyclonic circulation which are also marked LOW and HIGH, respectively. The point that it is now desired to bring out is that while we must always use the words LOW and HIGH on the weather map, the mistake must not be made of supposing that every LOW or HIGH depicted is a cyclone or an anticyclone, or that it is necessarily even the rudiments or inception of a typical system. We should recognize that frequently, especially in summer time, the configuration of the isobars is neutral or lacking in significance. There may be no definite relation between the subsequent weather condition and the particular existing pressure distribution. In these cases the real cause of subsequent phenomena must be sought in a study of detail, perhaps only remotely related to the configuration of the isobars or the presence of the semblance of lows and highs here and there.

It will perhaps always be impossible to draw the line definitely between LOWS that do and those that literally do not possess real cyclonic characteristics. In any case, it seems better to exclude these indefinite types from the rules that are appropriate for more or less typical maps and develop special rules for those that are lacking in definite significance. Similarly, these types should be carefully excluded in studies, statistical or otherwise, of storm tracks, velocities of motions, etc., since to include them is like mixing chaff with the wheat, and must necessarily warp the conclusions.

Inception of a system of cyclonic circulation (see figs. 2–5).—Authorities unreservedly assert that the invariable counterclockwise direction of motion in the Northern Hemisphere of inflowing winds in a region of low pressure is caused by the deflective influence due to the earth's rotation. This *ipse dixit* is generally accepted, but the detailed steps of the process are perhaps not fully understood, and a brief explanation seems therefore justified.

Meteorologists are not in accord as to the ultimate causes and the steps leading to a fully developed cyclone. A brief outline of the more important theories that have been advanced by high authorities is presented on pages 51–53, but it is impracticable to attempt a general analysis of these matters in this work. It is now proposed simply to show, step by step, how the characteristic counterclockwise circulation in a region of incipient low pressure soon becomes fully established.

No one knows, perhaps, just how typical cyclones begin, and for the present purposes we allow ourselves to assume (1) that, at the time and place of beginning, a condition of relative calm prevails

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over a considerable region; (2) that a condition of incipient low pressure also prevails.[1]

To depict such an incipient LOW on a weather map it may be necessary to draw isobars for only each thousandth or possibly for hundredths of an inch instead of the customary interval of tenths of an inch. The inflow of the surrounding air toward the center of this LOW will necessarily start along lines that cross the isobars directly at right angles, and the velocity will necessarily be small to correspond with the small pressure gradient. If the earth were at rest, other things remaining the same, the surrounding air masses would move directly in toward the center from all sides and either fill up the LOW, or, if portions of the air within were being carried upward by convection, then the inflow might or might not just sustain the upflow by convection. It is easy to see that a strictly radial flow of air into an incipient LOW of this character—and possibly ending in convection—is in reality an unstable state of dynamic equilibrium. It is like a pencil balanced upon its point. Slight disturbing influences may throw the air currents one way or the other so that gyratory inflow is very likely to begin sooner or later. Were the earth at rest there seems to be no special reason why the gyration should not be just as often in one direction as the other.

With the earth in rotation, however, the case is wholly changed. At latitude 30°, for example, a portion of air moving freely at a velocity of 1 mile per hour toward the center of low pressure will be turned to the right of its onward course in the Northern Hemisphere, and, unless otherwise prevented, will move in a small nearly closed circle less than 4 miles in diameter. It is important to note that the deflective influence of the earth's rotation acts with pronounced effect upon bodies moving freely at low velocities. Of course the air does not describe a complete circle or any considerable part thereof. Just as soon as its course cuts the isobars at some angle less than 90°, a component of the force due to the pressure gradient acts against the earth's deflective force and thus lessens in a measure the turning to the right. If a balance between these forces is reached, then the motion will be along straight lines, but such straight lines will cross the isobars in lines of flow leading *to the right* of the center of low pressure, and this species of flow can not adequately carry air into the region of lowest pressure to supply that lost by

[1] Local overheating, accompanied by convection, may be a possible cause of the incipient low pressure, but in the present analysis we do not undertake to say what it is that causes the incipient low pressure.

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convection, or whatever other cause is assumed to maintain the relatively low pressure which observations show grows and persists in typical cyclones. Since, for the reasons explained, air can not

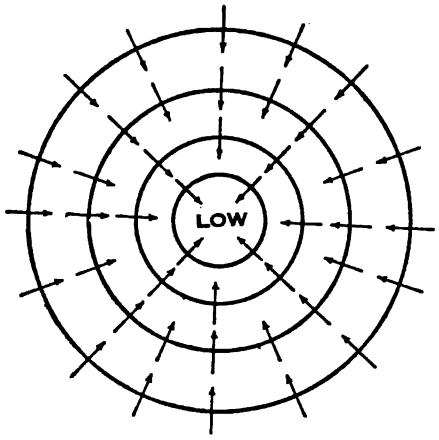

FIG. 2.—First stage: The inflow starts perpendicular to isobars, and might so continue on a nonrotating earth.

readily flow into the center of the region of incipient low pressure, the causes that are producing this LOW will tend to intensify the pressure gradient. This will have two effects, (1) to cause the flow to take place at a more rapid rate, (2) to lessen still further—indeed,

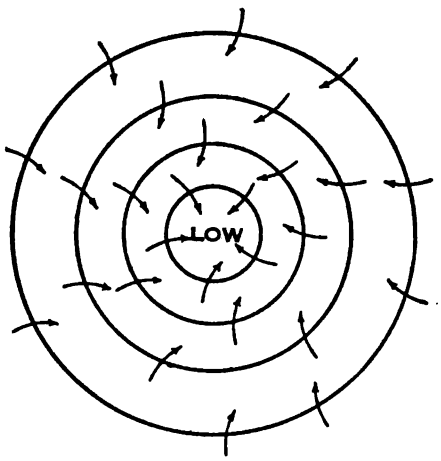

FIG. 3.—Second stage: Rotating earth. Crossing the isobars to the right of the perpendicular, the turning of the inflow still farther to the right is lessened or wholly prevented by a component of the force due to pressure gradient.

to prevent wholly—the turning of the winds to the right, and, instead, to deflect the winds strongly to the left. This left-hand deflection is produced by a component of the pressure gradient which, at this

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stage of the development, is now greater than the earth's *deflective force*. The *excess* in this case is in fact the centripetal force that

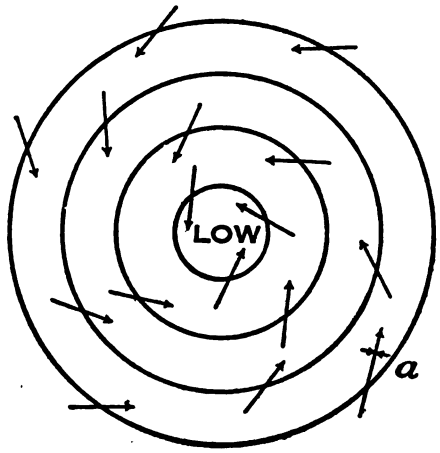

FIG. 4.—Third stage: The diverted inflow interferes with the rapid filling up of the low and induces a steeper pressure gradient, accompanied by higher velocities of inflow. Increased outward centrifugal tendency is overcome by the correspondingly greater component of the pressure gradient normal to the motion, as at *a*.

causes the path to curve to the left. The incipient flow has now become fully counterclockwise round the center of low pressure, and it is inconceivable that a condition of low pressure can form and attain any significant magnitude without quickly inducing the

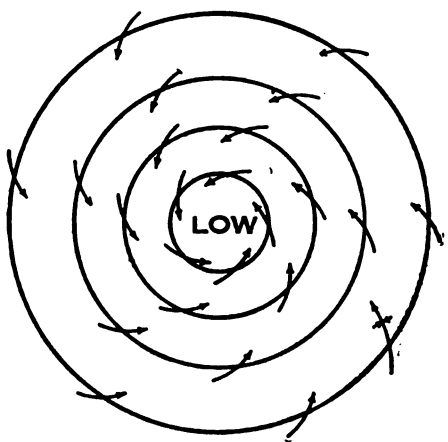

FIG. 5.—Equilibrium stage for nearly frictionless flow: In the free air the friction and resistances are at a minimum and the flow is there nearly parallel to the isobars. Under these conditions a small component of the gradient overcomes the frictional resistances and the remainder of the gradient force balances the earth's deflective influence and the centrifugal tendency.

counterclockwise circulation just described. The successive steps are graphically indicated in figures 2, 3, 4, and 5.

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In the foregoing it has been unnecessary to assume that the pressure gradient is steep or noticeably intense. Our object has been to show that the characteristic cyclonic circulation can be fully established with only an elementary or incipient condition of low pressure. All that is necessary is that the region of incipient low pressure be itself symmetrical and typical. Obviously, the inflow should sooner or later "fill up" the LOW, and doubtless this often occurs. Observations show, however, that cyclones in many cases grow in force, and attain tremendous intensity, which is maintained unabated for days in succession. Some explanation is needed, therefore, to show the source of the power required. One school of meteorologists, following Espy and Ferrel, has endeavored to show that the energy expended in cyclones in general is derived from the convective ascent of overheated, humid air, accompanied by condensation and precipitation of a portion of its moisture. The energy in such cases comes from the latent heat of condensation.

While difficulties are encountered in attempting to explain the genesis and maintenance of many of the fully developed cyclones of the middle latitudes by means of the convection theory, nevertheless that theory seems to account for the phenomena of the typical cyclones, hurricanes, typhoons, etc., of the tropical oceans. The reader must consult the original literature, however, for the full details.

Anticyclonic circulation.—Little needs to be said concerning the characteristic circulation of air in the anticyclone, as the whole system quite lacks the dynamic complexities that lend interest to the cyclone. The intense whirling motion at high velocities that is possible in the cyclone, accompanied by the steep pressure gradient and correspondingly low pressure at the center of a cyclone, are impossible combinations of conditions in an anticyclone. The cyclone may be relatively small in diameter, the winds of very high velocity, and the fall in pressure at the center 2 inches, or even more, below the normal; whereas the highest pressure in the anticyclone rarely exceeds 1 inch above the normal, and even in those cases the HIGH overspreads an area of very great geographic extent, so that the pressure gradient is in reality quite feeble and the wind velocities are of no great intensity. A brief examination of the manner of action of the forces controlling the anticyclonic circulation makes all this very clear.

Without attempting to explain how the condition of high pressure comes to exist in any given case, we assume that Figure 6 represents a typical HIGH. The fall of pressure outward from the center causes a corresponding outflow of air in all directions, which on a stationary earth would follow lines of flow perpendicular to the

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isobar. Such outflow, meeting no special obstruction of any kind, readily relieves any tendency there may be to accumulate an excess of air in the region in question. The comparatively free outflow prevents building up a great difference of pressure or steep pressure gradient. The air simply flows away too readily. Practically all this is equally true on the rotating earth, because the earth's deflective influence simply diverts the lines of flow slightly to the right, without materially obstructing the escape of the air from the center in all directions. Any close approach to a sustained whirling motion of outflowing air in a region of high pressure similar to the whirling inflow observed in storms like hurricanes seems quite impossible. The outward acting pressure gradient is the moving force and the lines of flow will be across the isobars, except as deflected slightly to the right in the Northern Hemisphere by the earth's deflective force. At *a* in

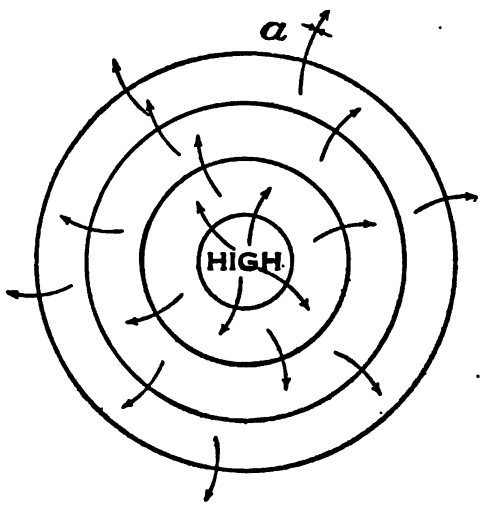

FIG. 6.—Anticyclonic circulation.

Figure 6 a line of flow is shown enlarged. The deflecting force acting to the right is due to the earth's rotative influence. It is completely neutralized by an equal and oppositely acting component of the pressure gradient. The air mass in question is free to move onward *in a straight line* and the component of the pressure gradient parallel to the line of flow sustains the motion. It is interesting to notice that air can not gyrate around a HIGH in a clockwise manner, parallel to the isobars that is at gradient velocity except at great distances from the center where the isobars are practically straight lines or even take on a reverse curvature, that is the air motion relative to the isobars is in reality counter clockwise or cyclonic.

In connection with questions both of cyclonic and of anticyclonic motions it must be recognized that the earth's deflective influence is

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altogether a passive force. This force is powerless to give any portion of air any motion whatsoever. Motion must be produced by pressure gradients or other forces, but when motion has been so originated or when sustained, then, and then only, does the deflective force operate. As we have seen, it tends partly to change the direction of motion or under certain circumstances, partly to accelerate or retard motion caused by other forces.

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CHAPTER II.

GENERAL CIRCULATION OF THE ATMOSPHERE.

By WILLIAM J. HUMPHREYS, Professor of Meteorological Physics.

Planetary winds	33	Hypotheses as to origin of extratropical cyclones	51
Monsoons	42	Extratropical cyclones	53
Trade winds	45	Anticyclones	60
Antitrade winds	46	Secondary winds	65
Tropical cyclones	47		

PLANETARY WINDS.

Normal state of the atmosphere.—The normal state of the atmosphere is one of motion, and observations show that the velocity is considerable. In middle latitudes, at least, this motion is from west to east more or less along parallels of latitude where the pressure gradient due to the zonal distribution of temperature overcomes resistances and neutralizes the rotative deflection of the earth. Calms in this region must be regarded as disturbed conditions of the atmosphere, and indeed often are comparatively shallow, with normal winds above.

General changes of wind with elevation.—Our knowledge of the directions and velocities of the winds of the earth is still fragmentary and incomplete. Over large areas even the surface winds are unknown, and over the regions best studied these alone are fairly well known. The continuous records obtained at mountain stations have added much to our knowledge of air movements, but stations of this nature are comparatively few, and their data, however valuable, are always affected to an unknown extent by local topography. Cloud observations have also given a large amount of valuable information, but these, too, are only fragmentary. Cloud observations give simply the direction and velocity of the air at one level, and even these can not be obtained for the stratosphere, since this region is never visited by clouds. In many respects kites and sounding balloons have furnished the most valuable data in regard to the movements of the upper air and their causes. Unfortunately, however, aerological investigations of this nature, with relatively few

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exceptions, have been restricted to the Northern Hemisphere, and even there mainly to the summer season.

From these various sources of information a number of tentative conclusions, subject of course to modification, have already been reached in regard to the winds of different parts of the world from the surface of the earth to great elevations. Some of the more important of these conclusions are:

1. That there is no continuous and rapid overflow of the high atmosphere all the way from the equatorial to the polar regions. At an elevation of 10 kilometers, for instance, the wind of middle northern latitudes seems to have southerly components about as often as northerly.

From this it follows that the overflow theory of equator-polar circulation must be either abandoned or at least profoundly modified.

2. That the equatorial winds are not always and at all levels from the East. That on the contrary west winds occur (how regularly is uncertain) at elevations of about 18 to 20 kilometers, with east winds again prevailing (certainly at times) at still greater elevations.

The cause of this layer of equatorial west wind has never been explained. Indeed, it may be only a local and temporary phenomenon.

3. That layers of air in which the temperature is approximately constant or even increases with increase of elevation often exist at different levels, especially through the first 2 or 3 kilometers. This temporary stratified condition of the lower atmosphere appears to be universal. It is found even over tropical oceans and is exceedingly well developed over the ice plateau of Antarctica.

These layers usually show such different humidities and such different wind velocities from those of the adjacent layers as to indicate a distinct origin. A rising convection current on reaching its equilibrium level flows away substantially at that particular elevation and obviously retains its own humidity, provided condensation has not taken place, as well as its dust content and other characteristics. Its viscosity is not the same as that of the adjacent air because its humidity or temperature, or both, is different. These considerations and the evidence presented by billow clouds, indicate that any such layer with a distinctly independent velocity tends to retain its integrity and to glide over another from which it differs physically, without rapid intermingling. Both reflection from and evaporation of clouds are causes of temperature and humidity irregularities or stratification of the atmosphere. Clearly, then, one should expect in the lower atmosphere substantially the kind and amount of temperature inversions and other irregularities actually found from observation.

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4. That the upper-air winds are exceedingly variable along the edges of the high-pressure belts, and that marked disturbances occur in the antitrades.

5. That the poleward pressure gradient in the upper atmosphere becomes very small long before the Arctic Circle is reached—in fact, is small between 50° and 60° N.

6. That in high latitudes where the poleward pressure gradient of the upper atmosphere is small, the westerly winds are not constant.

Velocity of wind at different elevations.—That the wind increases with increase of elevation, at least for a considerable distance above the surface of the earth, is accepted as a fact in a general way by almost everyone. Measurements, whether made by triangulation on such freely drifting objects as clouds and balloons, or by anemometry on the relatively stationary kite, fully support this impression.

Near the surface of the earth the wind velocity increases rapidly with increase of elevation, but at a rate that, other things being equal, increases with velocity but decreases with height. Up to from 5 to 25 feet, or 2 to 8 meters, above the surface, depending upon the actual velocity, the increase of average velocity is very rapid, but the wind exceedingly irregular and puffy. Above this level the increase of velocity is more regular, so that the approximate velocity at any height up to 50 feet, or 16 meters, may be computed[1] from the observed velocities at some other height by the empirical equation,

$$V = v\sqrt{\frac{H+72}{h+72}},$$

in which V is the velocity of the wind at the height H, computed from the known velocity v at the height h. Both elevations are expressed in feet.

Other empirical equations between wind velocities and elevations have been given for greater heights. Douglass,[2] for instance, finds his observations between 100 meters and 600 meters fairly well satisfied by the simple equation,

$$\frac{V}{v} = \left(\frac{H}{h}\right)^{\frac{1}{4}}.$$

Shaw[3] suggests, as a likely formula,

$$V = \frac{H+a}{a} V_o,$$

in which V is the wind velocity at the height H above *ground*, V_o the observed anemometer velocity and a a constant, obviously depend-

[1] Stevenson, Jr. Scot. Metr. Soc., V., p. 348, 1880.
[2] Nature, 33, p. 593, 1885.
[3] Advisory Committee for Aeronautics, Reports and Memoranda, No. 9, p. 8, 1909.

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ing upon surrounding topography, anemometer exposure and, perhaps, other factors.

Among the most interesting observations on the relation of wind velocity to altitude are those of Dr. Cesare Fabris[1], based on some 200 pilot balloon flights made at nearly equal intervals during the year June, 1910–May, 1911, at Vigna di Valle, principal aerological station of the royal Italian oceanographic committee. The coordinates of this station are: N. 42° 04′ 41″; E. 12° 12′ 43″; altitude 272.4 meters. It is, therefore, about 25 miles northwest of Rome.

The general results of all the observations are summed up in figure 7, which shows four distinct regions:

(*a*) The region of rapid linear increase of velocity with increase of altitude; extending from the surface (272 meters), where the velocity is least, from 300 to 400 meters above. This is a universal phenomenon, and the region of its occurrence obviously that in which the winds are affected by surface friction and the resulting turbulence. Clearly, too, the average number of eddies and their consequent effect on velocity must rapidly decrease with increase of elevation, substantially as indicated by the given velocity-altitude curves.

(*b*) The region of velocity decrease with increase of altitude, about 200 meters thick and coming immediately above *a*. This decrease of velocity probably is due to the mixing of two wind layers, an upper and a lower, moving in very different directions, and therefore a local and temporary rather than a universal phenomenon.

(*c*) A region of irregular winds slowly increasing with increase of altitude, extending from about 500 to 1,500 meters above ground. This is a very general phenomenon[2] probably due to that frequent convectional mixing induced by insolation and, at night, by cloud evaporation.

(*d*) A region of approximately constant increase of velocity with increase of elevation, beginning at about 1,500 meters above the surface and extending to at least the maximum height observed, 5,000 meters. The wind velocities of this region are determined by prevailing horizontal pressure gradients, as will be more fully explained below.

Cloud and balloon observations show that this increase of wind velocity with increase of altitude above 1,500 to 2,000 meters elevation, holds practically to the top of the troposphere where the velocity in middle latitudes may amount to as much as 200 miles per hour (90 meters per second), or even more.

Above this level, that is, in the stratosphere, the average velocity is decidedly less.

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[1] R. Comitato Talassografico Italiano, Memoria 8, pp. 37–46, 1912.
[2] Berson, Wissenschaftliche Luftfahrten, 3 p. 205, 1900.

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These facts are all well known, but there do not appear to be very generally accepted and satisfactory discussions of the reasons why the average wind velocity at levels above the limit of appreciable surface influence should go on increasing with increase of

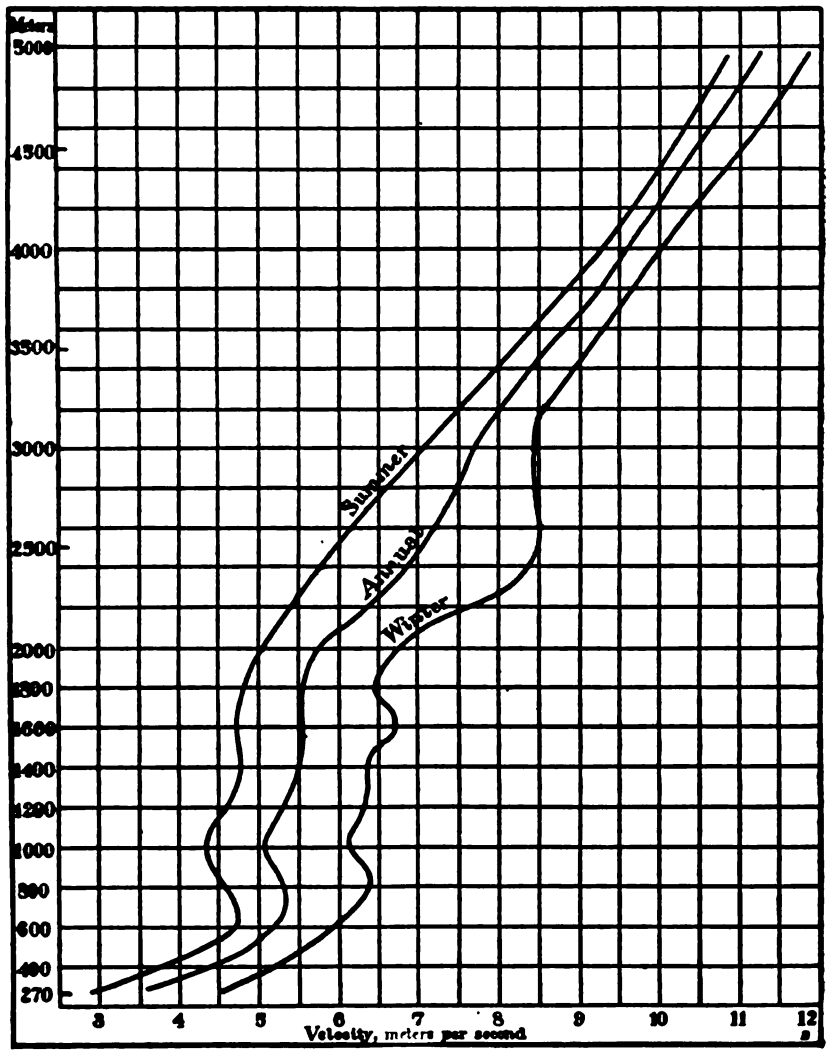

FIG. 7.—Annual, summer, and winter, wind velocities, with altitude.

elevation up to the isothermal level, and then decrease. Data sufficient for a complete solution of this problem are not available, but enough facts are known to indicate quite clearly each link in the chain of cause and effect that determines the average atmospheric movements in middle and higher latitudes.

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Because of the distribution of insolation over the earth, the temperature of the lower atmosphere, as we know from observation, is warmest, on the average, in equatorial regions and coldest beyond the polar circles, with intermediate values over middle latitudes. Hence, since the temperature of the air above the earth depends mainly upon the convection and radiation from below, it follows that the latitude distribution of temperature in the upper air must be

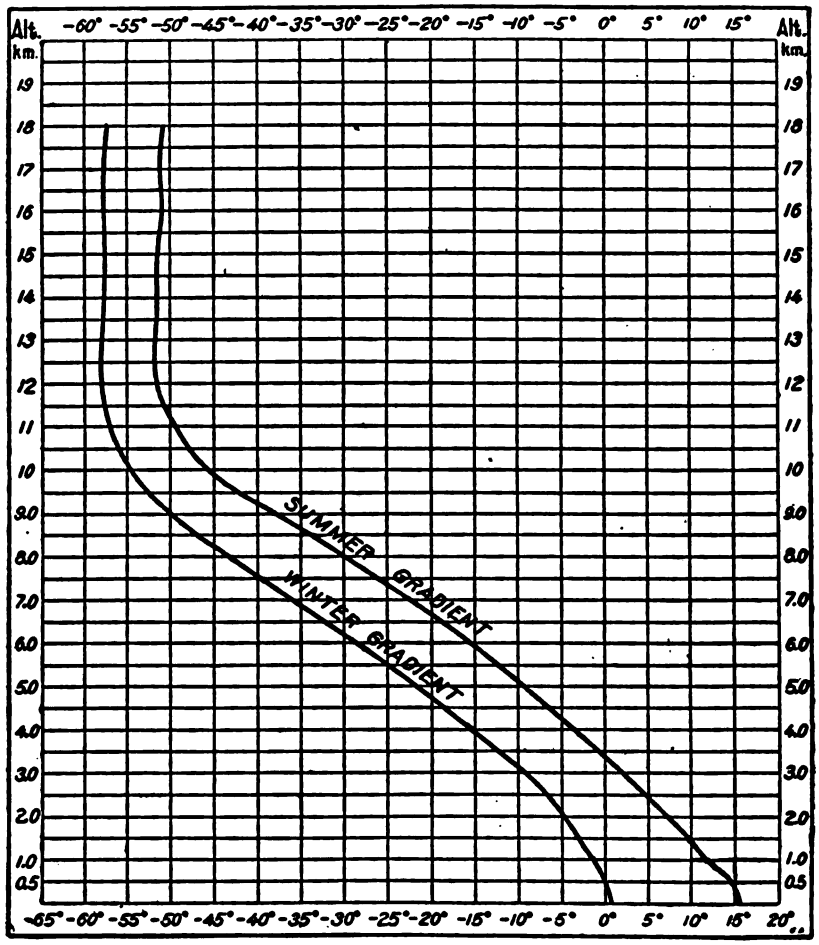

FIG. 8.—Winter and summer vertical temperature gradients, in degrees C.

substantially the same as that at the surface; that is, warmest within the Tropics and coldest in polar regions, with intermediate values between. And this, indeed, is the latitude distribution of temperature at each level of the atmosphere up to 10 to 12 kilometers, or through fully three-fourths of its mass. At much higher levels, 15 to 20 kilometers, for reasons that need not be discussed here, the

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rare atmosphere is coldest over equatorial regions and warmest over high latitudes. This inverse condition, however, does not apply to the winter and summer atmospheres of the same place, nor of neighboring places on approximately the same latitude. This is shown by figure 8, which gives the average winter and summer vertical temperature distribution as determined respectively by 52 and 65 sounding balloon flights at Munich, Strassburg, Trappes, and Uccle. Here the summer atmosphere, as shown by figure 8, is warmest and the winter atmosphere coldest all the way to the greatest altitudes explored, and probably much higher, presumably as far as the atmosphere has any appreciable density.

A study of the influence of the temperature distribution in the free air on the horizontal pressure gradient leads the writer to conclude that throughout the region of the free air from somewhat below the height of 5 kilometers to somewhat above that of 10 kilometers *the horizontal pressure gradient maintained by the temperature difference between adjacent regions is approximately constant with a tendency toward a maximum gradient at about 8 kilometers, roughly.* As a direct consequence of this theorem, the winds in the free air above about 5 kilometers should steadily increase to a maximum at about 8 kilometers and decrease thereafter. The argument in support of this[1] will not be given here, as space is not available.

The above general conclusions are in full accord with the average temperature distribution in the atmosphere and the resulting horizontal pressure gradients as shown, respectively, by figures 9 and 10, copied from Süring's paper[2] on the present state of knowledge concerning the general circulation of the atmosphere.

Both figures refer to the northern hemisphere during its summer.

Since the horizontal pressure gradients caused by the temperature differences under discussion are at right angles to the isotherms, or, theoretically, along meridians, it follows that the isobars in the free air must approximately follow parallels of latitude. The tendency of the winds in the free air to follow the isobars (in the present case to run along parallels of latitude) is explained below. In nature, however, this tendency is opposed by friction and resistances of every kind, including the powerful effects of convection. A deflection of the course of the wind in the direction of the pressure gradient always exists, since resistances of some kind are always present. Consequently, the winds will actually tend always to cross the isobars (parallels of latitude in this case), and interzonal flow must necessarily follow, roughly proportionate to the resistances mentioned. In full accord with this, observations show that planetary isotherms and general winds more nearly follow parallels of

[1] Monthly Weather Review: 41; 14–17.
[2] Zeitschrift der Gesel. für Erdkunde, p. 600, 1913.

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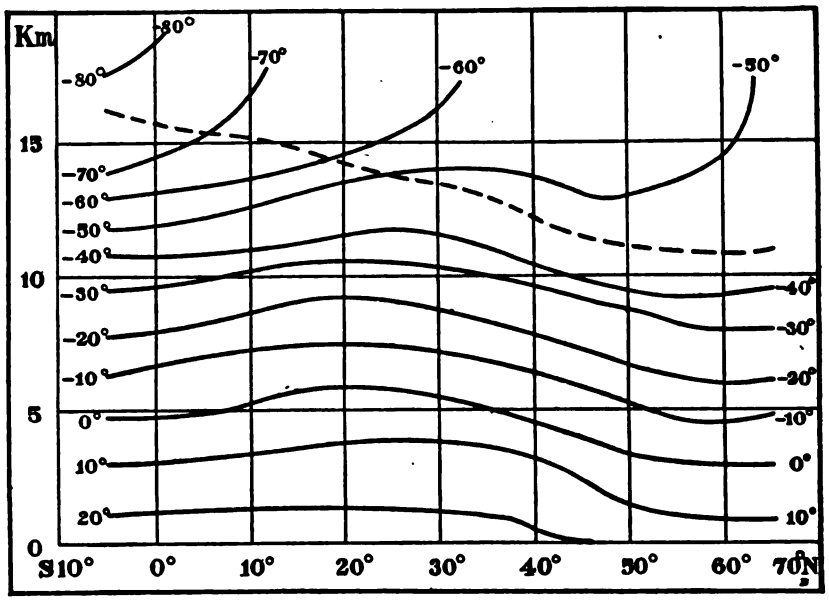

FIG. 9.—Temperature distribution (degrees C.) with altitude.

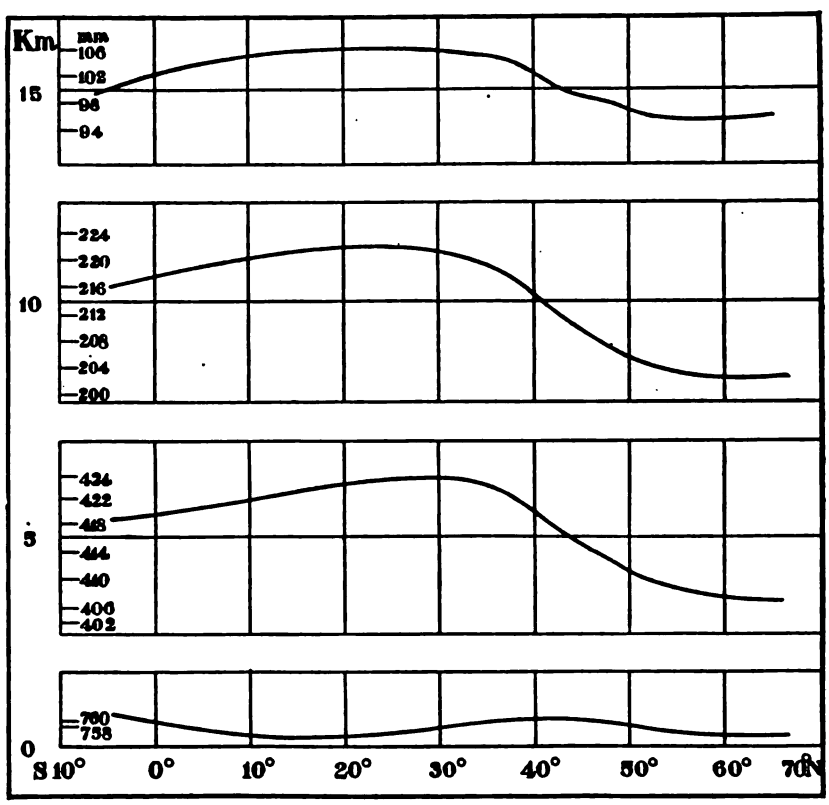

FIG. 10.—Pressure distribution with altitude.

The heavy broken line in Fig. 9 represents, approximately, the lower limit of the stratosphere.

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latitude in the southern hemisphere, where much the greater portion of the surface is uniform, than in the northern, where the surface is far more diversified. Likewise, interzonal circulation with all its attendant irregularities of weather and climatic contrasts along the same parallel of latitude are more pronounced in the northern hemisphere than in the southern.

Season of greatest wind velocity.—From the above discussion it is obvious that the general wind will be swiftest whenever the temperature contrast between the air of higher and lower latitudes is greatest. But the temperature of the atmosphere in low latitudes does not change through the year nearly so much as does that of higher latitudes. Hence the maximum horizontal temperature gradient, and, therefore, the maximum pressure gradient and maximum winds, must occur during winter.

Latitude of greatest wind velocity.—The latitude of greatest winds clearly is that at which the horizontal pressure gradient is greatest. In the northern hemisphere this, according to figure 10, occurs in the summer at about latitude 45°. It is obvious, however, since this pressure gradient depends in general upon the latitude rate of temperature change, that the belt of highest winds must shift more or less from season to season—poleward with coming of summer, equatorward with onset of winter.

Equatorial east to west winds.—East to west winds are quite as general and constant in equatorial regions as are west to east winds in middle latitudes. Along its borders, roughly 30° N. and 30° S., this equatorial belt of east to west winds is very shallow. Toward the Equator its thickness increases as a rule until it reaches at least the limit of vertical convection. There are, however, great irregularities in this belt of winds, just as in those of higher latitudes on either side of it. Some explanation of the general conditions just stated may be offered.

Several influences act to cause general latitudinal motions of the atmosphere, such, for example, as a very small possible east to west motion due to the tidal action of the sun and moon or a similar very small seemingly west to east motion that can be attributed to the diurnal changes of temperature and the consequent unsymmetrical positions of the points of simultaneous maximum and minimum temperature on a given latitude. Interzonal circulation, however, is the most obvious cause of east to west and west to east general or planetary winds, and, indeed, is usually regarded as the sole cause of such winds. Air moving away from the Equator in the upper strata is deflected eastward by the rotative deflection; hence such air on reaching the temperate zones appears as a west to east wind. Similarly, surface air moving toward the Equator is deflected toward the west and in the equatorial regions would become an east

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to west wind. A detailed explanation of all the principal features of the general motions of the atmosphere that would be generally satisfactory in all respects is probably not yet available, and, in any case, is hardly appropriate in this work. It may be stated generally, however, (1) that the primary or fundamental circulation of the atmosphere is interzonal, due to differences in temperature between the regions of high and low latitude; (2) that this interzonal circulation, through the rotation of the earth, causes the prevailing west to east winds of middle and higher latitudes and the east to west winds of equatorial regions; and (3) that the velocities of these winds depend ultimately upon the general pressure distribution and the frictional resistances of all kinds.

In addition to the primary circulation of the atmosphere as a whole there are several secondary circulations or wind systems of magnitude sufficient to bring them markedly under the influence of the earth's rotation. It will be convenient next to consider some of the more important of these winds.

MONSOONS.

Summer monsoons and winter monsoons—for convenience discussed under the same head—bear the same relation to summer and winter that sea breezes and land breezes bear to day and night. It is the temperature contrast between land and water that establishes the circulation that manifests itself on the surface as a sea or land breeze in the one case, and as a seasonal or monsoon wind in the other. Always the direction of the surface wind is from the cooler toward the warmer of the adjacent regions—from the ocean toward the land by day as a sea breeze and during the warmer season as a summer monsoon; from the land toward the ocean by night as a land breeze and during the colder season as a winter monsoon. Hence, monsoons may be regarded as sea and land breezes of seasonal duration, and might very well be classed with the latter under some common appropriate caption. However, because of the immense areas involved, it can not be said of them, as of sea and land breezes, that they are caused by local temperature differences. Besides, the duration of a land or sea breeze is so short that it covers only a narrow strip along the coast, while the monsoon winds extend far from the coast, both inland and to sea. The directions of the former, since their paths are always short, are but little affected by the rotation of the earth, while the directions of the latter are greatly affected by this important factor.

The prevailing directions of monsoon winds, except where distinctly modified by the general circulation, are given in the following table and in figures 11 and 12.

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Direction of monsoon winds.

Hemisphere.	Season.	Land south.	Land west.	Land north.	Land east.
Northern	Summer	NE	SE	SW	NW.
	Winter	SW	NW	NE	SE.
Southern	Summer	NW	NE	SE	SW.
	Winter	SE	SW	NW	NE.

Since monsoons depend upon seasonal temperature contrasts between land and water, it is obvious that winds of this class must be

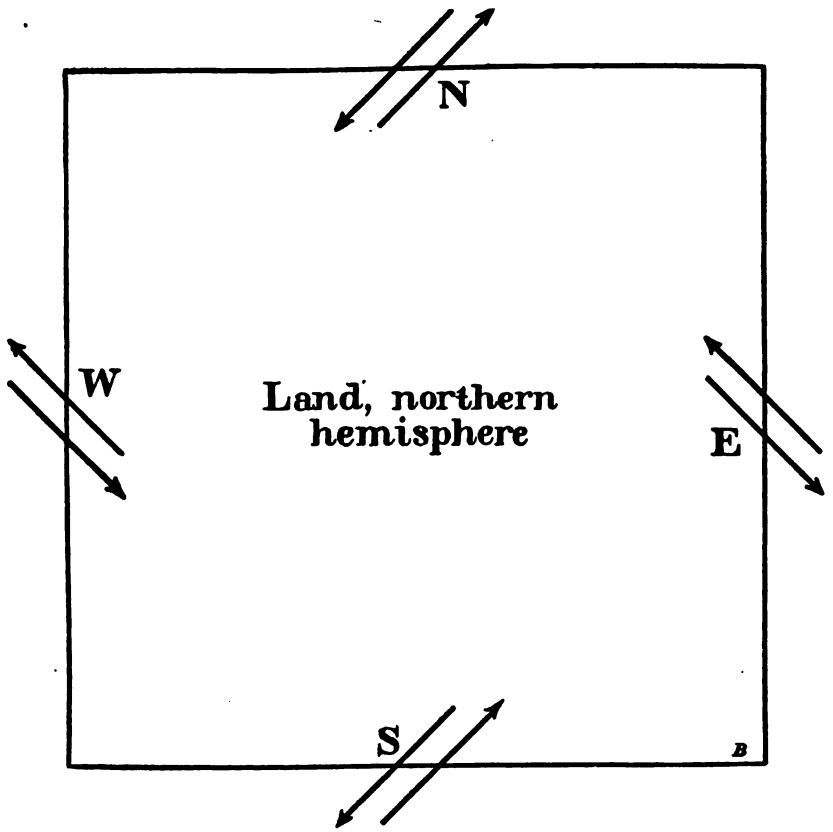

FIG. 11.—Prevailing direction of monsoon winds.

most pronounced where such contrasts are greatest, that is, in temperate regions, and least developed where the temperature contrasts are smallest, or in equatorial and polar regions. It is even possible for secondary monsoons to develop, or for a monsoon to occur within a monsoon. This merely requires a favorably situated inland sea, such as the Caspian. In such cases monsoons, or seasonal winds, obtain between the inland sea and the surrounding land and, in turn, between the continent as a whole and the adjacent oceans, just as on

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a still greater scale they must constantly exist between the perpetually warm equatorial regions and those about the poles which are continually cold.

Another comparison between these several winds, the semidaily (land and sea breeze), semiannual (monsoon), and planetary (interzonal), that is interesting and instructive concerns their depth. Land and sea breezes seldom reach greater depths than 100 meters

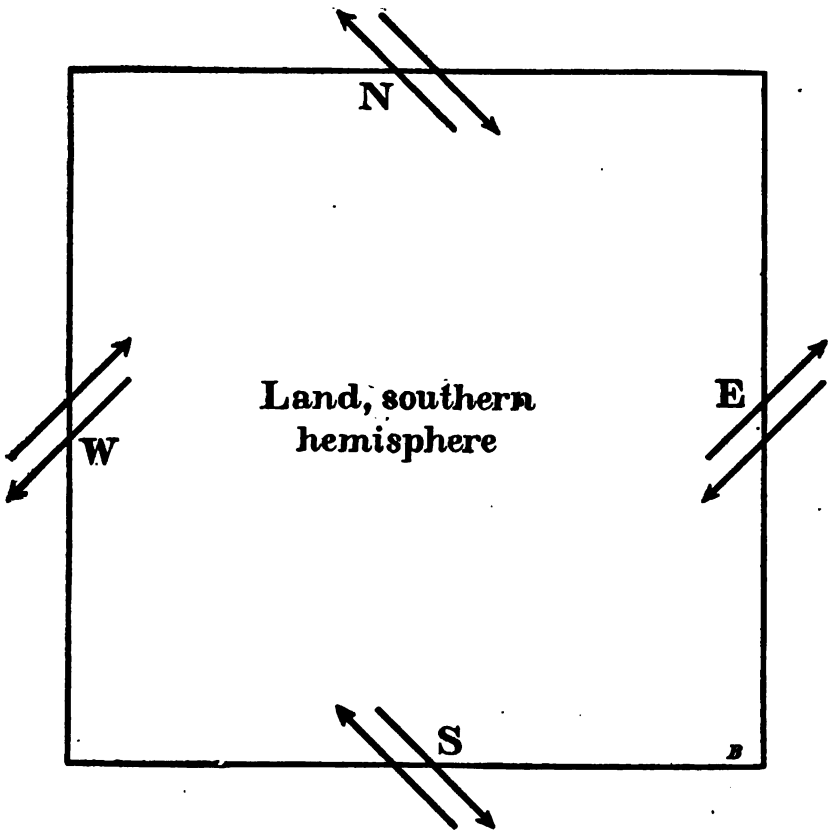

FIG. 12.—Prevailing direction of monsoon winds.

to 500 meters; the winter monsoon of India has a depth, roughly, of 2,000 meters and the summer monsoon of 5,000 meters, while the general or interzonal circulation involves the whole of the troposphere with a depth of 10 to 12 kilometers, and probably also, though perhaps to a less vigorous extent, even the stratosphere.

If the term "monsoon" be extended, as it properly should, to include all winds whose prevailing directions and velocities undergo distinct alterations as a result of seasonal changes in temperature, it

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clearly follows that this class of winds is well nigh universal. Nevertheless, it is generally thought of only in connection with those places where it is most strongly developed, and especially where the seasonal winds are more or less oppositely directed. Among these places are India (Indian monsoons are the most pronounced of all and have been most fully studied), China, the Caspian Sea, Australia, and portions of Africa.

In the United States the chief monsoon effects are the change in the eastern portion from prevailing northwest winds of winter to southwest winds of summer and the change in Texas and the Plains States from northwest in winter to southeast in summer.

TRADE WINDS.

As already explained, in equatorial regions, or, roughly, between latitudes 30° N. and 30° S., the winds usually have an east-to-west direction. In the Northern Hemisphere they blow rather constantly from the northeast, becoming east-northeast and finally nearly east winds as the equator is approached. Similarly, in the Southern Hemisphere the trade winds are southeast, becoming east-southeast and finally nearly east. In each case they blow trade—that is, in a fixed or nearly fixed direction. It is because of this steadiness of direction and not because of any relation they may have to the paths of commerce that they are called trade winds. Along each border of this belt, or along both the northern and southern horse latitudes, calms are frequent, while such winds as do occur are generally light and variable in direction. Besides, the barometric pressure is high, humidity low, and sky clear. Hence it generally is inferred that throughout the horse latitudes the air is descending. This evidence, however, as applied to places other than the centers of maximum pressure, is not quite conclusive; it only shows that the air is not ascending.

Another narrow belt of calms or light, variable winds, known as the region of the doldrums, approximately follows the equator, where the two systems of trade winds, the northern and the southern, come together. Here, however, the barometric pressure is low, humidity high, and sky often filled with cumulus and other clouds that give conclusive proof of strong ascending currents.

Trade winds in the sense here used—that is, nearly constant winds blowing in an east-to-west direction—do not occur on land, except along coasts and over islands. They are mostly phenomena peculiar to the oceans, and even there are different from ocean to ocean, and also, since they tend to follow the thermal equator, somewhat different in latitude and intensity from season to season.

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According to Shaw, the average velocities of the Atlantic trade winds are as follows:

Trade-wind velocities, Atlantic Ocean.

[Miles per hour.]

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
NE. trade	11.9	13.0	12.5	13.4	12.3	11.4	10.3	8.3	9.6	7.4	9.8	11.6	10.5
SE. trade	14.1	13.0	13.0	12.1	11.0	12.1	12.1	15.0	17.0	15.0	16.1	15.0	13.9

From this it appears that the trades are strongest during the winter when their counterpart, the system of westerly winds of higher latitudes, is strongest; and weakest during the summer when their counterpart is weakest. It also appears that the southeast trades, or those pertaining to the Southern Hemisphere are about one-third stronger than the northeast trades. This probably is due to the fact that the westerly winds of the Southern Hemisphere are stronger, on the average, than the westerlies of the Northern Hemisphere.

The trade winds of the Pacific Ocean are weaker than those of the Atlantic and not so constant in direction. On the Indian Ocean the trades are confined to the Southern Hemisphere. North of the Equator the winds of this ocean, being controlled by the adjacent continent, are distinctly of the monsoon type.

The seasonal shifting in latitude of the trade regions and belt of doldrums is shown by the following table, copied from Hann's Lehrbuch, third edition, page 463.

Seasonal latitude limits of trade winds and doldrums.

	March.		September.	
	Atlantic.	Pacific.	Atlantic.	Pacific.
NE. trade	26°–3° N.	25°–5° N.	35°–11° N.	30°–10° N.
Doldrums	3° N.–equator	5°–3° N.	11°–3° N.	10°–7° N.
SE. trade	Equator–26° S.	3° N.–28° S.	3° N.–25° S.	7° N.–20° S.

ANTITRADE WINDS.

As the heated and expanded air of equatorial regions overflows to higher latitudes it necessarily is deflected by the rotation of the earth. That portion which goes north changes from an east wind near the Equator to a southeast, south, southwest, and finally at about latitude 35° N., a more nearly west wind. Similarly that portion which goes south becomes a northeast, north, northwest, and finally, at about latitude 30° S., a more nearly west wind.

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At great altitudes, 10 to 15 kilometers, near the Equator the east to west velocity is of the order of 80 miles per hour (36 meters per second). Hence its west to east velocity around the axis of the earth is about 957 miles per hour. As this air moves to higher latitudes its west to east velocity must so increase, according to the law of conservation of areas, that at about 16° N. or S. its angular velocity will be the same as that of the earth, and itself, therefore, be moving only poleward in the plane of the meridian. When the thermal equator is removed from the geographical equator the place of poleward winds is also more or less shifted to higher latitudes. Thus during August and September, when the center of the doldrums is, roughly, 8° N., the inflection of the antitrades should occur somewhere between latitudes 20° N. and 25° N. At other seasons when the doldrums are nearer the Equator the place of inflection should also be less removed. At still higher latitudes these upper or antitrade winds become westerly, and therefore, except as modified by local disturbances, tend, as previously explained, to reach a limiting or gradient velocity and to follow parallels of latitude. However, there are innumerable disturbances, mainly due to the distribution of land and water, that cause constant and abundant interzonal circulation which feeds and indefinitely maintains the antitrade wind portion of the general or planetary atmospheric circulation.

The depth of the trade winds or the height of the under surface of the antitrades is greatest during summer and least during winter. It also decreases with latitude, reaching the surface, as already explained, at about 30° N. and S. During winter the height over Cuba, 22° N., is about 3.5 kilometers; over Jamaica, 17° N., 6.5 kilometers; over Trinidad, 12° N., 8 kilometers; and over Hawaii, 19° 30′ N., about 3 kilometers.

Indeed the trade winds as they approach the Equator also ascend and gradually flow off poleward, thus producing a great overflow or antitrade branch of the circulation, which in turn becomes the general westerlies of higher latitudes. These in their turn are dissipated by storms and other local disturbances, but after few or many vicissitudes, as circumstances may determine, ultimately return to a somewhat similar starting point. Thus the circulation is perpetual, in which any round from lower to higher latitudes and return is similar to, but in general by no means a duplicate of any other. There is a general similarity in these cycles of circulation, just as one tree is similar to another, but they present, as do the trees, an endless variety of detail.

TROPICAL CYCLONES.

A tropical syclone—the cyclone of the Indian Seas, the hurricane of the West Indies and South Pacific, and the typhoon of the West

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Pacific and China Sea—consists of a vast whirl of rapidly moving air currents surrounding a calm and relatively small center or vortex.

Distinction between tropical and extratropical cyclones.—Although tropical and extratropical cyclones have many similarities, such as low pressure centers, abundant precipitation, same instantaneous wind directions, and the like, and although it may be impossible to say just when a tropical cyclone on its way to higher latitudes becomes extratropical, nevertheless they usually differ from each other in several important respects. Among these differences are: (*a*) The isobars of the tropical cyclone usually are more symmetrical and more nearly circular than those of the extratropical; (*b*) the temperature distribution around the vortex of the tropical cyclone is practically the same in every direction, while about the extratropical it is very different; (*c*) in tropical cyclones rains are torrential and more or less equally distributed on all sides of the center, in the extratropical rains usually are much lighter and very unequal in different quadrants; (*d*) tropical cyclones usually have calm rainless centers, 5 to 30 miles or more in diameter, while the extratropical rarely shows this characteristic whirl phenomenon; (*e*) tropical cyclones are most frequent during summer of the hemisphere in which they occur, while the extratropical are strongest and most numerous during winter; (*f*) tropical cyclones often move to higher latitudes, where they assume, more or less completely, characteristics of the extratropical cyclone. The extratropical cyclone, on the other hand, never invades the regions of the tropical nor assumes its distinctive characteristics; (*g*) the pressure drop of the tropical cyclone generally begins with the winds, in the extratropical it usually begins much sooner (*h*) the tropical cyclone has no anticyclone companion, the extratropical usually has—to the west.

Place of occurrence.—Tropical cyclones occur over the tropical portions of all oceans except, possibly, the South Atlantic. They are most numerous in the West Atlantic, including the Gulf of Mexico, Bay or Sea of Bengal, and West Pacific, including the China Sea, where their annual frequencies are, roughly, about 4, 8, and 24, respectively. They seldom originate closer than 5° or 6° to the Equator, but most frequently between latitudes 10° and 20°. In fact, they seem to originate almost entirely along the belt of doldrums, and, therefore, since this belt follows the sun, to appear at higher latitudes during summer, and lower, or not at all, during winter.

Size and shape.—The diameter of tropical cyclones vary greatly. Initially such storms may be no more than 50 miles across, while when well developed they may have diameters of 200 to 500 miles.

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The clouded area incident to typhoons, always much more extensive than the surface storm, may be even 1,000 miles across.

The shape of the cyclone, as given by the isobars, appears usually to be that of an ellipse whose diameters are to each other, roughly, as 2 to 3, with the longer axis in the direction of travel.

Direction of wind.—The direction of the surface wind is spirally in at an angle of 30°, roughly, to the isobars, counterclockwise in the Northern Hemisphere, clockwise in the Southern. At an elevation of only 700 to 800 meters the inflow is said to cease, and above this level the winds are spirally out. These horizontal motions also necessitate a correspondingly strong upward component around the vortex or inner portion of the storm, and a slower downward component over a much greater surrounding area.

Velocity of wind.—The velocity of the wind varies greatly in different tropical cyclones and even more greatly in different portions of the same storm. Near the center, or within the eye of the storm, which may have any diameter from 5 to 30 miles or more, the wind is very light and the sky clear or only partially covered with high clouds. Away from this center, especially on the poleward side, the winds often reach destructive velocities of 100 to 125 or even 150 miles an hour, but decrease in violence rather rapidly with increase of distance from the center, dropping to only moderate winds of 30 to 40 miles an hour at a distance of, say, 200 miles.

Direction of travel.—Tropical cyclones of the Northern Hemisphere first move west then usually northwest. Many turn north at latitude 20° to 25°, roughly, and finally move away to the northeast. In the Southern Hemisphere the corresponding directions of travel of the tropical cyclone are: West, southwest, south, and finally southeast.

Velocity of travel.—The velocity with which tropical cyclones travel varies from almost zero in certain cases, especially at or near the place of inflection when this happens to be abrupt, to, perhaps, 500 miles a day. Over the Bay of Bengal, Arabian Sea, and China Sea the velocity averages about 200 miles a day. Over the south Indian Ocean the velocity ranges from 50 to 200 miles a day. Over the west Atlantic the average velocity before and during recurvature is about 260 miles a day, but after recurvature—that is, when moving northeast over middle latitudes—about 400 miles per day.

Origin and maintenance.—Tropical cyclones originate in a belt or region of doldrums where convectional rains are frequent and heavy. They rarely occur closer than within 5° or 6° of the Equator, and both vertical convection and earth rotation contribute to their mechanism.

The atmosphere of a doldrum belt becomes very warm and humid, and therefore frequently is in a state of vertical convection. The

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upward branches of this convection are nearly always limited to very restricted areas, where they break through, as it were, and give rise to local thunderstorms. Occasionally, however, heating and expansion must take place more or less uniformly over a comparatively extended region. So long as the upward current is gentle and restricted to a small area, the compensating inflow from the sides is also gentle and can produce only a cumulus cloud and, perhaps, a thunderstorm. In the event that such a storm is formed the inflowing counter current to the ascending warm air is replaced by an equivalent column or sheet of descending cold air immediately to the rear of the ascending; that is, the loss of warm surface air is compensated by an equally concentrated and vigorous downflow of cold upper air. Hence rotary circulation, since it depends upon horizontal inflow from all, or at least several, sides, is not possible in the case of ordinary thunderstorms, whatever their location.

On the other hand, an approximately equal expansion of air over a relatively large area, whether caused by an increase of temperature, or vapor density, or both, must lead to an overflow above and a corresponding surface inflow around the outer borders.

Obviously the rate of volume overflow at any time is proportional to the area in question, while the corresponding inflow is proportional to the boundary multiplied by the average normal component of the wind. If the area is circular with radius R, it follows that the rate of outflow above is proportional to ΠR^2, and the rate of inflow below to $V_n 2\Pi R$, in which V_n is the average radially inward component of the wind at the distance R from the center. But as the two currents compensate each other, except as modified by precipitation, explained below, it follows that V_n, other things being equal, is proportional to R. Hence when the area involved is rather large, 100 miles, say, in diameter, the relatively shallow and spirally moving compensating or return current may become very perceptible. This at once feeds the entire rising column with excessively humid air. Hence, it becomes an even better absorber than before of both insolation and terrestrial radiation, and, therefore, is likely even to increase its rate of expansion. Hence, widespread condensation may soon begin. If so, the latent heat thus set free, while it does not actually raise the temperature of the air, reduces the rate of adiabatic cooling from approximately 1° C. to about 0°.4 C. per 100 meters increase of elevation, and thereby establishes within the rising column temperatures distinctly higher than those of the surrounding air at the same level. In this way the circulation is accelerated, and thereby the rate of condensation and freeing of latent heat increased, until, through growth of size, restricted supply of water vapor, and other causes, a limiting but somewhat steady state is reached.

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When the conditions here described occur at some distance from the equator, the rotation of the earth deflects the inflowing air and establishes a rotation around the region of lowest pressure, a result obviously accentuated whenever it takes place, as occasionally it may, between the borders of more or less oppositely directed trade systems. As the air flows in, under the law of the conservation of areas, its angular momentum remains constant, except as diminished by friction and viscosity. Hence, since surface drag is most effective at but small elevations, the atmosphere at only 100 to 200 meters above the water may, as it moves inwards, soon reach a velocity at which the pressure gradient overcomes the resistances of motion and balances the centrifugal tendency and the earth's deflective force.

When such velocity is reached, as it obviously may be at any appreciable altitude, inflow at that place necessarily ceases. Near the water, however, this limiting velocity is prevented by surface friction. Hence, as soon as the whirl is well established it must be fed almost exclusively by the lowest and, therefore, most humid air. In this way a maximum amount of precipitation, and, through it, a maximum amount of storm-sustaining thermal energy, is secured.

That the energy supplied by condensation is essential to the maintenance of the tropical cyclone is evident from the fact that there is a tendency for it to go to pieces over dry land, especially before it has recurved, or wherever precipitation fails.

Of course similar atmospheric expansions may, and doubtless do, occur in the doldrums when they are on or very close to the equator. In this case, however, a whirl is impossible, and therefore a LOW so initiated will soon fill by gentle, somewhat radial, winds from all sides and at considerable altitudes, or, at most, mere local thunderstorms will develop.

From the above, it is evident that the seat, so to speak, of the tropical cyclone is where the sustaining energy is supplied; that is, where condensation is taking place. Hence, the movement of the air at this level, and not at the surface, determines the course of the storm, and even carries it athwart shallow surface winds.

Hypotheses as to the origin of extra-tropical cyclones.—It may be profitable to mention one or more of the principal hypotheses that have been advanced from time to time to account for the origin of cyclones and anticyclones.

The convectional hypothesis, as put forth and elaborated by Ferrel, postulates that in consequence of the differences in density due to differences in temperature in a horizontal direction a convectional interchange of air between the areas of different temperatures arises and there result differences in pressure, and, consequently, cyclones.[1]

[1] For the details of this theory see "A Popular Treatise on the Winds," Ferrel, pp. 227–241.

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The driven eddy hypothesis.—This hypothesis, first enunciated by von Hann, is as follows:

The forces which set up the atmospheric circulation of the higher latitudes, especially in winter, have their origin in the warmth of the tropics—that is to say, in the difference of temperature between the polar regions and the equatorial zone. Cyclones and anticyclones are but partial phases of the general circulation of the atmosphere. The air-currents that set toward the poles as a consequence of the upper gradients are partially resolved in vortices in the higher latitudes, and their progressive movement is chiefly determined by the prevailing westerly direction of the wind currents. The influences of variations of the terrestrial surface, of the heating and cooling of continents and oceans, as well as of the local influx of water vapor and its condensation, are but of secondary importance. They may, however, strengthen or destroy the ascending or descending eddies, and modify their paths and their rate of progression. (Nature, Nov. 6, 1890, p. 16.)

Prof. Davis,[1] in discussing the merits of the convection and driven eddy hypotheses, respectively, says:

If, on the other hand, cyclonic and anticyclonic disturbances are produced by the irregular flow of the general winds, it is probable that these disturbances would originate in the higher regions of the atmosphere where the winds blow much faster than on the earth's surface. The differences of pressure at high altitudes would be felt down to sea level, and, as the lower winds move with comparative slowness, they would be governed by the gradients thus imposed on them by the irregular movements of the upper winds. According to this theory, an area of high pressure would be perceived at sea level beneath a district where the upper currents crowd together; and an area of low pressure or a cyclonic storm would be developed beneath a region where the upper currents are somewhat divergent.

The counter current hypothesis.—Prof. Milham gives this hypothesis, as follows:[2]

The region of strongest air currents, and thus most vigorous exchange of air between Equator and pole, seems to be at an elevation of about 1.5 miles above the earth's surface. Suppose that there are two great air currents at this level flowing side by side but of opposite direction and of very different temperature, the one on the right being warm and flowing poleward and the one on the left being cold and flowing equatorward. Due to this difference of temperature, at the earth's surface there will exist an area of low pressure with spirally inflowing winds turning counterclockwise in the northern hemisphere. The truth of these statements becomes evident when the structure of a LOW above the earth's surface as given in section 288 is considered. It was there shown that the atmospheric whirl which exists at the earth's surface degenerates at a height of a little more than a mile into two counter currents flowing in different directions with very different temperatures. The converse is equally true. Two currents in the upper atmosphere necessitate a LOW with inflowing winds at the earth's surface. A LOW, then, with its spirally inflowing winds may be considered simply as the surface effect of two powerful counter currents of very different temperature in the upper atmosphere. Since the exchange of air between Equator and pole is more vigorous in winter than in summer, the

[1] Elementary Meteorology, 1894, p. 219–220.
[2] Meteorology, Milham, New York, 1912, p. 311.

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number and intensity of LOWS should be greater in winter than in summer. This theory, then, seems to meet all the observed facts, to be free from objections, and to be plausible, but not so easy to picture as some of the other theories.

The above quotations are given for whatever they may be worth. The author is frank to say, however, that none of them conveys to him any clear and workable conception of the origin, mechanism, or maintenance of the extratropical cyclone.

Extratropical cyclones.—The strong winds and heavy precipitations of middle latitudes are associated with the occurrence of low barometric pressure, while gentle winds and clear skies are as commonly associated with the occurrence of high barometric pressure. Hence cyclones, or that system of winds that accompany and surround a region of minimum pressure, and anticyclones, or that system of winds that follows and delimits a region of maximum pressure, deserve and have received a vast amount of observation and study. Nevertheless, in many respects—in their origin, in their temperature distributions, and in the laws of their movements—cyclones and anticyclones in great measure still remain the meteorological mysteries they have always been.

Although cyclones and anticyclones are as closely associated and as fully the complements of each other as are hills and hollows, it nevertheless will be convenient to consider them independently.

Size.—The area covered by a cyclone, the largest of all distinctive storms, nearly always amounts to more than a million of square miles. In North America the average diameter of these storms is estimated to be roughly 1,500 miles. Over the North Atlantic their diameters are still larger. In other parts of the world substantially the same great magnitudes obtain; in fact, the semipermanent or winter Aleutian low appears usually to be much larger than the traveling cyclones of the Atlantic or even the great semipermanent Icelandic LOW.

Direction of movement of cyclonic center.—The direction in which the center of a cyclone travels, wherever it may be located, is substantially the same as that of the higher clouds or of the atmosphere at 6 to 10 kilometers above sea level. In general, therefore, the cyclones of middle latitudes move from west to east, with a southerly dip over continents and a northerly deflection over oceans.

Locus of maximum cyclonic frequency.—Probably no part of the earth's surface more than 3° or 4° from the Equator is wholly free from cyclonic storms. The frequency of their occurrence, however, varies greatly with respect to both time and place. Beginning with the West Pacific, during summer and fall many cyclonic storms come from the general region of the Philippines and move northeast across or on either side of Japan. Winter and spring cyclones enter on this

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same general course at latitudes 30° to 40°, some presumably being of oceanic origin, while others obviously either develop within or cross over China. In any case the general track of these storms is along the Japanese and Kurile Islands, thence east over the Bering Sea. The main path is then southeast across the Gulf of Alaska, with the cyclones, including offshoots from the Aleutian LOW, crossing over the continent anywhere between latitudes 40° and 60°, but apparently most frequently in the general neighborhood of Vancouver Island, 50° N. These Pacific LOWS usually cross the continent nearly from west to east, dipping slightly south over the Great Lakes, and finally leave it by way of Newfoundland. A smaller number of cyclones from the North Pacific dip far south, somewhat like the Mediterranean branch, to about latitudes 35° to 40°, but usually recurve west of the Mississippi and join the main course as they reach the Atlantic. Those cyclones that originate in or cross over Central and Southern United States, or the Gulf of Mexico, move northeast and gradually merge their paths with that of the Pacific cyclones anywhere from the Great Lakes to the Newfoundland Banks. Other cyclones coming up from the Florida and West Indian regions follow the coast, not far offshore, and also merge their paths with that of the others in the neighborhood of Newfoundland. Half way or more across the Atlantic the path of maximum storm frequency breaks up into at least three distinct branches. The main branch turns far north mainly by way of the Norwegian Sea, then southeast, entering Russia in the neighborhood of the White Sea, and passing on toward central Asia. A second branch turns southeast and crosses Europe, mainly along the northern side of the Mediterranean, and then turns north either across Austria toward northwest Russia or by way of the Black Sea toward central Asia. A third and least branch appears usually to lie just south of Ireland, and to cross both the North and the Baltic Seas, and then, like the others, to move on toward Siberia and central Asia.

The cyclonic storms of central and northern Asia do not appear to be very numerous. Nevertheless, their track of maximum frequency seems to turn south, as it does over North America, as far as Lake Baikal, thence probably to the Sea of Okhotsk and across or to the south of Kamchatka to the main storm path north of the Aleutians, as already explained.

In the Southern Hemisphere the path of maximum storm frequency appears to follow closely the 60° parallel of latitude. Presumably, the path dips poleward at both the Ross and the Weddell Seas, as each of these are regions of semipermanent low pressure.

It must be remembered, however, that in both the Southern Hemisphere and the Northern, cyclonic storms occur almost everywhere,

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and therefore the paths or routes above described are only those of maximum cyclonic frequency, and not paths of exclusive travel.

Velocity of travel.—The velocity with which the center of a cyclonic storm moves along its path varies greatly. It depends upon the season, being fastest in winter and slowest in summer; upon location, being faster in America than in Europe, for instance; and, finally, upon the individual storm.

The following table gives average velocities for different parts of the Northern Hemisphere. Those pertaining to the United States are computed from a table of average 24-hour movements as determined by Bowie and Weightman[1] from 16,239 observations, covering the years 1892–1912, inclusive. The others are from Hann's Lehrbuch der Meteorologie, third edition, page 518.

Average velocity of cyclones in meters per second.

[For the United States the velocity is also given in miles per hour.]

	United States.		Japan.	Russia.	North Atlantic.	West Europe.	Bering Sea.
Winter	13.4	(29.9)	12.4	10.8	8.2	8.0	8.5
Spring	10.6	(23.7)	11.1	9.2	8.3	7.2	8.5
Summer	9.3	(20.7)	7.8	8.0	7.4	6.6	10.3
Fall	11.0	(24.5)	10.6	9.6	8.3	8.2	9.3
Year	11.1	(24.7)	10.5	9.4	8.05	7.5	9.1

Frequency.—The frequency of the occurrence of cyclonic storms varies not only from place to place, as already explained, but also, at any given place, or even over an extensive area, probably an entire hemisphere, according to season. Tropical cyclones, it will be recalled, are far more frequent during summer and early fall than during winter. Mid-latitude cyclones, on the other hand, have exactly the opposite relation of frequency to season, being, in general, most numerous in winter and least numerous in summer. Exceptions to this rule apply to the paths of tropical cyclones next after the recurvature, provided we regard such storms as having then become extratropical. Perhaps exceptions also apply to certain regions on the poleward sides of the main cyclonic routes, since these are farthest north in summer and farthest south in winter. This, however, is not certain. A statistical investigation might show that even the greatest increase due to latitude shift is more than compensated by the general seasonal decrease in frequency.

When all LOWS that appear in the United States or southern Canada, whether short or long lived, weak or intense, are counted, it appears[2] that the frequency of summer (June, July, and August) LOWS is to that of winter (December, January, and February) LOWS

[1] Monthly Weather Review, Supplement No. 1, p. 8, 1914.
[2] Bowie and Weightman, Monthly Weather Review, Supplement No. 1, p. 7, 1914.

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approximately as 5 to 8. On the other hand, if only long-lived cyclones are considered, it appears[1] that in the United States the frequencies of summer to winter storms are only about as 2 to 9 and those of Europe as 3 to 10.

In either case, then, that is, whether only the longer lived and more intense cyclonic storms are counted or whether all of whatever magnitude and duration are included, it seems that they are most frequent during winter and least frequent during summer. Furthermore, the extratropical cyclones of winter are not only more numerous than those of summer but also, in general, longer lived, more intense, and faster moving.

Direction of winds.—From the directions of winds in and about a region of low barometric pressure, as given on synoptic charts, it is often inferred that cyclonic winds circulate spirally inward and upward and then outward around a storm axis, counter clockwise in the northern hemisphere, clockwise in the southern. This indeed is, in general, the course of the winds in tropical cyclones, especially when violent and of small diameter, as the eye of the storm and directions of cloud movements clearly indicate, but it does not apply to extratropical cyclones, except perhaps occasionally to one of exceptional violence and small diameter. Extratropical cyclones rarely have clear centers, as they would if the circulation about them was closed or along spiral paths of repeated turns. Neither is a closed circulation indicated by the movements of the clouds. Again, it often happens that the velocity of the forward-moving wind of a cyclone is less than that of the storm itself, so that instead of flowing around the storm center it necessarily is left behind.

Synoptic weather maps show instantaneous wind directions, which represent wind paths only when the storm as a whole is stationary.

The main body of the storm winds, those below an elevation of 5 or 6 kilometers, except near the surface, move at any instant roughly parallel to the isobars. That is, each air mass moves approximately at right angles to the direction of the horizontal pressure gradient. This does not mean that the path of any given particle is around and around the center of low pressure, because this center itself and its system of isobars are both in rapid transit. Near the surface the velocity is so slowed down that the deflection forces no longer balance the horizontal pressure gradient and the winds of this level are directed inward across the isobars.

Deviation from isobars.—The angle between the surface wind direction at any place within a cyclonic storm and the isobars is least, *a*, when the winds are swiftest—therefore least to the south and east of the storm center and greatest to the north and west; *b*, when the

[1] U. S. Weather Bureau Bulletin A, p. 6, 1893.

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velocity of the storm as a whole is least, consequently in the summer time, because during this season the storm movement is less than during other seasons; *c*, over water, where it is roughly 10°, because the surface drag is less here than over land, where the deviation averages 40° to 50°.

It is important to note also that usually the deviation does not greatly change with distance from the center. This follows from the fact that the wind velocity and the horizontal pressure gradient both are roughly constant in any given direction from the center, so long as only points distinctly within the storm area are considered.

With increase of elevation and consequent decrease of surface drag, the deviation from the isobars decreases by 25° or 30° in the first kilometer. Beyond this elevation it still decreases, but relatively very slowly. At an elevation of several kilometers the velocity of the air is decidedly greater than that of the storm, and, therefore, air that may have risen to this level is carried forward. Hence, the main outflow of the extratropical cyclone is toward the east.

Wind velocity.—The strongest upper winds of the extratropical cyclone are on its south and west sides, where the isobars are most crowded and where the direction of the winds is substantially that of the storm movement.

The actual velocity of the wind in the different quadrants of a cyclone and at different elevations is given in the following table by Peppler,[1] based on a large number of measurements made during 1903–1908 at Lindenburg; latitude, 52° 10′ N.; longitude, 14° 15′ E. Probably other mid-latitude regions have approximately the same cyclonic wind velocities. This, however, is not certain, nor are there available sufficient data for determining the question.

Convection.—The movements of the air in the vertical, in an extratropical cyclone, or between such a cyclone and a neighboring anticyclone are not known with much detail and accuracy. However, since the cyclone moves eastward with the air currents directed inward across the isobars, it is obvious that ordinarily the chief air convergence, due in part to increase of latitude, and therefore principal vertical convection, must be on the front or east side. Temperature also usually helps to locate the chief upflow in this quadrant, since its winds necessarily are from lower latitudes.

This localization of the uprising air explains why, other things being equal, most of the precipitation due to cyclonic storms occurs to the east and southeast (northeast in the Southern Hemisphere) of the center.

[1] Beiträge zur Physik der freien Atmosphäre, 4, p. 95, 1911.

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Cyclonic wind velocity in meters per second and (miles per hour).

Altitude.	Surface 122 m.	500 m.	1,000 m.	1,500 m.	2,000 m.	2,500 m.	3,000 m.	3,500 m.	4,000 m.
South quadrant:									
Winter	6.16	14.75	15.09	15.32	15.79	16.85	18.28	19.25	20.30
	(13.8)	(33.0)	(33.8)	(34.2)	(35.3)	(37.7)	(40.9)	(43.1)	(45.4)
Summer	5.42	9.64	10.69	11.31	12.22	12.91	14.06	15.69	17.21
	(12.1)	(21.6)	(23.9)	(25.3)	(27.3)	(28.9)	(31.5)	(35.1)	(38.5)
Year	5.84	12.24	12.93	13.38	14.07	14.94	16.24	17.53	18.81
	(13.1)	(27.4)	(29.0)	(30.0)	(31.4)	(33.4)	(36.3)	(39.2)	(42.1)
West quadrant:									
Winter	6.70	13.47	13.39	13.93	14.75	16.18	17.31	17.81	.....
	(15.0)	(30.1)	(30.0)	(31.2)	(33.0)	(36.2)	(38.7)	(38.7)	.....
Summer	5.66	9.45	9.89	9.91	10.17	10.65	11.40	12.07	12.63
	(12.7)	(21.2)	(22.1)	(22.1)	(22.7)	(23.8)	(25.5)	(27.0)	(28.2)
Year	6.06	11.34	11.52	11.80	12.34	13.29	14.23	14.56	.....
	(13.5)	(25.4)	(25.7)	(26.4)	(27.6)	(29.8)	(31.9)	(32.6)	.....
North quadrant:									
Winter	4.72	8.85	8.95	9.00	9.09	9.07	9.32	8.52	8.02
	(10.5)	(19.8)	(20.0)	(20.1)	(20.4)	(20.3)	(20.8)	(19.0)	(17.9)
Summer	4.84	7.85	8.37	8.45	8.81	9.11	10.26	10.63	10.63
	(10.8)	(17.6)	(18.7)	(18.9)	(19.7)	(20.4)	(22.9)	(23.8)	(23.8)
Year	4.79	8.36	8.66	8.72	8.94	9.08	9.78	9.57	9.32
	(10.7)	(18.7)	(19.4)	(19.5)	(20.0)	(20.3)	(21.9)	(21.4)	(20.8)
East quadrant:									
Winter	4.50	10.45	10.02	10.43	10.58	11.64	12.11	13.37	14.59
	(10.1)	(23.4)	(22.4)	(23.4)	(23.7)	(26.0)	(27.1)	(29.9)	(32.7)
Summer	4.11	8.22	8.64	8.77	8.98	9.50	9.50	9.81	11.86
	(9.2)	(18.4)	(19.3)	(19.6)	(20.1)	(21.3)	(21.3)	(21.9)	(26.5)
Year	4.34	9.37	9.37	9.64	9.82	10.61	10.84	11.62	13.25
	(9.7)	(20.9)	(20.9)	(21.6)	(21.9)	(23.7)	(24.3)	(26.0)	(29.7)

Other things, however, are not always equal. Thus, an extensive plain rising gradually to great elevations may slope in such direction that the mechanical or forced convection over it on one side of a cyclonic center may approach or even exceed the thermal convection to the east. The Great Plains east of the Rocky Mountains illustrate this point. Here precipitation, in the case of "stagnant" or slow-moving LOWS, usually is most pronounced to the north of the center where the winds are persistently up the slope. This is an extreme case, but it suffices to show that a rule relating to shifting winds and clear or foul weather that applies well in one place may not apply at all in another.

Semipermanent.—The name, semipermanent cyclone, or semipermanent LOW, has been given to that system of winds of any region over which the barometric pressure habitually or seasonally averages lower than for the surrounding regions. The term generally is used as though it applied to but one and the same cyclone, however much it may shift in position or even for a time wholly disappear. Thus we say *the* Icelandic LOW not *an* Icelandic LOW. Similarly, we say *the* Aleutian LOW not *an* Aleutian LOW. But, as stated, this applies only to average conditions. In reality there is no one permanent Icelandic LOW, for instance, that retains its identity wherever it may be, but only a series of sluggish or temporarily fixed LOWS, all of which form at or invade practically the same restricted region.

There are several such regions of semipermanent cyclones in various parts of the world. The most nearly permanent, at least in the Northern Hemisphere, and at all times one of the most productive, lies

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southeast of Greenland and southwest of Iceland. Another such region, active during winters only, lies along and to the south and southeast of the Aleutians extending to and including the Gulf of Alaska; the Norwegian Sea and, possibly, the Sea of Okhotsk are other such high-latitude regions. The Gulf of Lyon is a low-pressure haunt during the winter, as is also the Black Sea and the Caspian Sea, as its monsoon winds definitely show. The Gulf of Mexico, over which occasional winter cyclones appear to generate, may likewise be added to the above list.

In the Southern Hemisphere the regions of most persistent LOWS are the Ross Sea and its counterpart, the Weddell Sea, on the other side of the continent.

All the above-named regions have surfaces warmer than those that surround them. The circulation thus induced, acted upon by the deflective force due to the earth's rotation, necessarily becomes a system of cyclonic winds. Thus the warm waters off the coast of Greenland and Iceland necessarily maintain the atmosphere above at higher temperatures, level for level, than those over the neighboring ice caps. Hence, practically a continuous overflow of air from the one place, with compensating drainage and inflow from the other, is enforced by the existing and perpetually maintained distribution of unequal surface temperatures. During the winter, when these temperature contrasts are most pronounced, the resulting Icelandic LOW is most intense, but it prevails through summer also, and for the simple reason that the necessary temperature gradients though weakened, are neither obliterated nor reversed—the water remains always warm in comparison with the ice caps of both Greenland and Iceland, which persist from season to season and from year to year.

The Aleutian LOW, on the other hand, is merely seasonal. It prevails only while the adjacent Alaskan and Siberian regions are snow covered and relatively cold. When this snow is gone the temperature gradients are even reversed and the offshore drainage of winter is replaced by the onshore winds of summer.

Obvious similar considerations and explanations apply to all the other regions frequented by semipermanent cyclones.

Permanent lows.—There are two well-developed, permanent LOWS, and also a third imperfectly developed. These are: (*a*) The equatorial LOW, which roughly follows the equator through its entire course, due partly to the relatively high temperature of this belt and partly to the right and left deflective forces of the westward winds of the Northern and Southern Hemispheres, respectively. (*b*) The Antarctic trough, encircling Antarctica generally between 60° and 70° S. and having an annual average pressure of about 740 millimeters. This LOW is mechanically sustained jointly by the swift west winds over the oceans and the east to west component of the

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southeast winds from Antarctica. (*c*) The Arctic trough, analogous to the Antarctic trough but less symmetrical and apparently only fragmentary.

Migratory cyclones.—The great majority of extratropical cyclonic storms are migratory, as a rule breaking off apparently from or in some manner being induced by the semipermanent LOWS, but occasionally forming at almost any other place, especially along the more frequented storm paths. The genesis, the development, and the detailed structure of these storms are by no means obvious nor well understood. Discussions of these features are to be found in meteorological literature generally, but are hardly appropriate here.

ANTICYCLONES.

These great wind systems are in many respects counterparts and in some cases traveling companions of the cyclones. The barometric pressure is high and the gyratory motion of the winds is clockwise in the Northern Hemisphere and the reverse in the Southern. For convenience in subsequent discussion in the interests of forecasting anticyclones will be classified as follows: Permanent; semipermanent; migratory.

Permanent anticyclones.—Certain beltlike regions of relatively high barometric pressure encircle the earth along the borders between trade winds and the west winds of adjacent higher latitudes—that is, at about 30° to 35° north and south latitudes. Although of different character from place to place and showing some variations, these belts are always recognized as permanent HIGHS. They are best developed over the oceans, where the trade winds upon which they seem to depend are strongest and steadiest. These belts are shown in figure 13.

In addition to the belts just mentioned there are two extensive regions, Antarctica and Greenland, where the barometric pressure is always high. At each place the high pressure appears to be the result of the very low prevailing temperatures, which in turn are due in part to the great elevations and in part to the free and abundant radiation from the snow surface through the comparatively clear skies—kept generally free from clouds by the descent of the upper air induced and maintained by the lower circulation. That surface radiation is an essential factor in establishing and maintaining these low temperatures is highly probable.

The monsoonlike flow of air masses resulting from the great temperature contrasts described is manifest in those strong and persistent southeast or anticyclonic winds that characterize the climates of the border and all explored portions of Antarctica except, of course, near the pole, and presumably, therefore, of the whole con-

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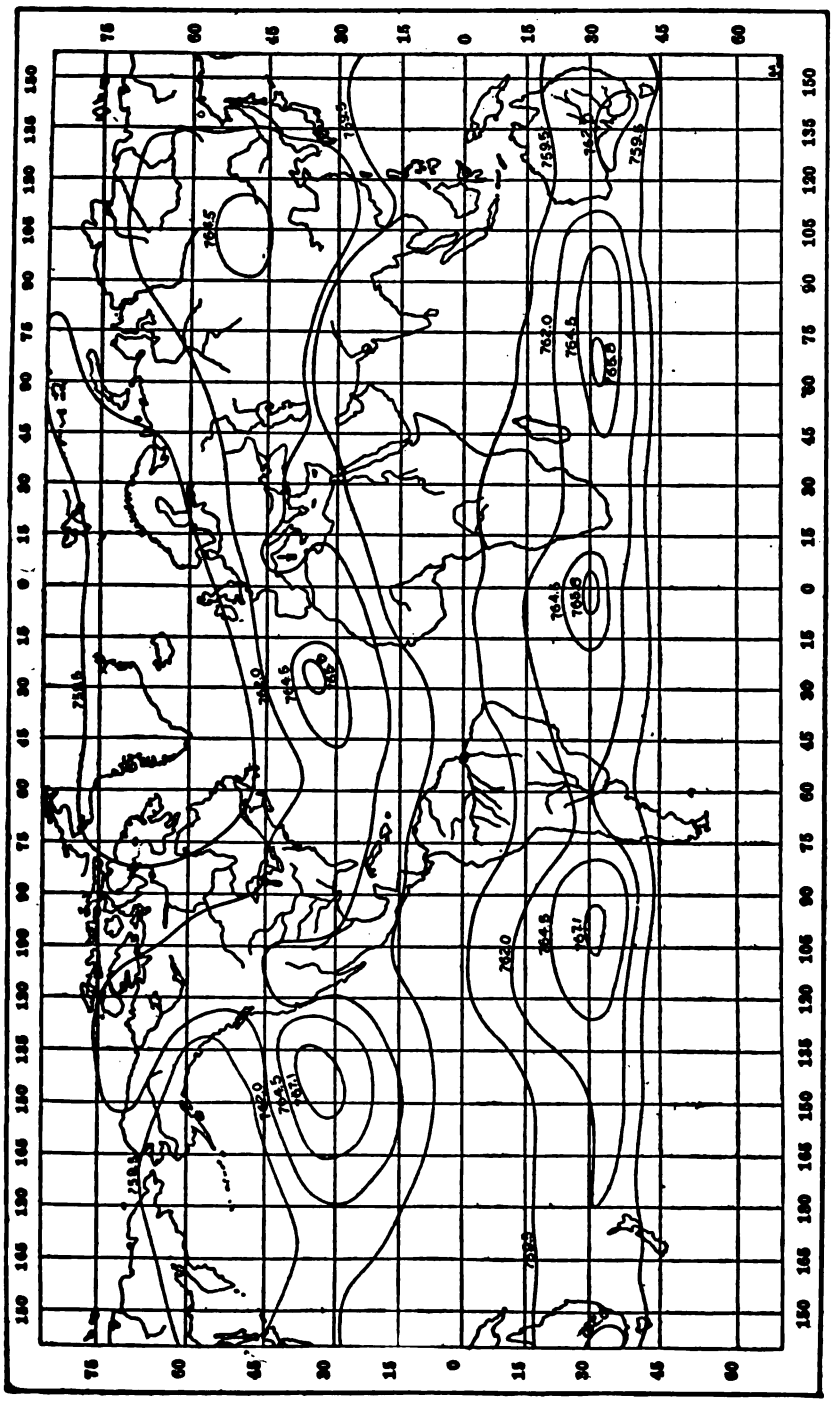

FIG. 13.—Average Annual Isobars.

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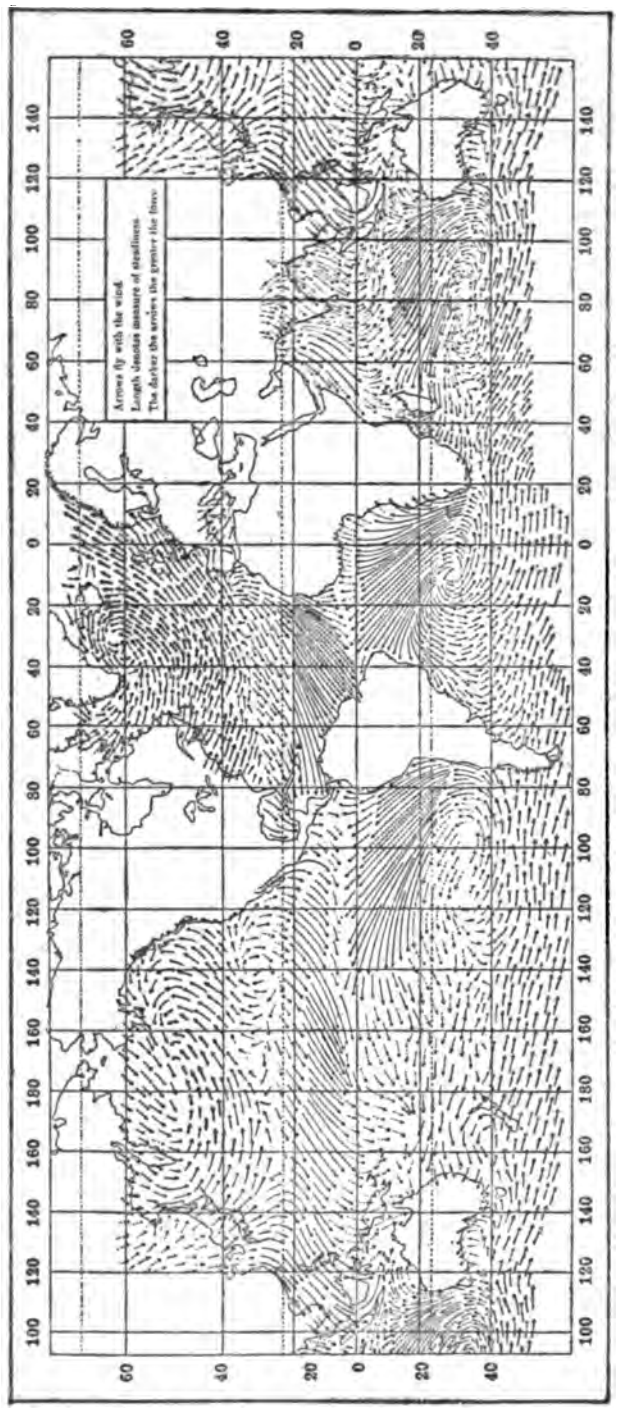

FIG. 14.—Ocean winds, January and February.

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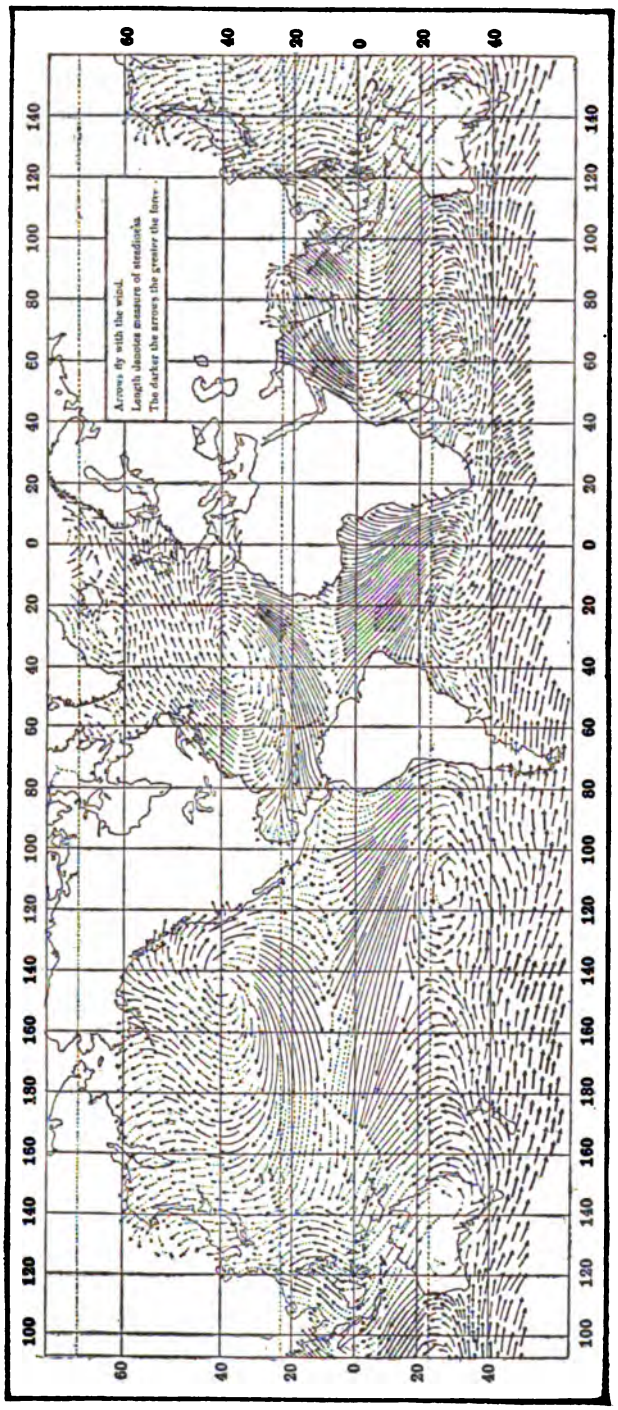

FIG. 15.—Ocean winds, July and August.

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tinent. Similar, though less vigorous, anticyclonic winds also prevail over and around Greenland.

Each of these great regions, but especially Antarctica, by virtue of its strong and continuous refrigerative effect, obviously is exceedingly effective in its influence on the atmospheric circulation of its respective hemisphere. If there were no such extensive high and snow-covered areas in the polar regions, it is clear that our general circulation would be less vigorous and doubtless very different in many places.

Semipermanent anticyclones.—As is well known, there are five semipermanent HIGHS, all of which occur on the oceans, two, as figure 13 shows, about 35° north of the equator and three about 32° south of it. Two are on the Pacific Ocean, one west of southern California, the other off the coast of Chile; two on the Atlantic Ocean, near the Azores (known as the Azores HIGH) and off the coast of southern Africa; and one on the Indian Ocean about halfway between Africa and Australia. A sixth oceanic HIGH of this same class, but far less persistent than any of the above, often develops, especially during winter, in the region of the Bermudas.

There appears to be a close relation between the intensities and locations of these HIGHS and the directions and velocities of the surrounding winds, even to great distances, as shown by figures 14 and 15.

Migratory.—The anticyclone to be considered here is the common one of middle latitudes. The directions of its system of winds, but in no sense the complete paths of the air particles, are spirally outward—clockwise in the Northern Hemisphere, counterclockwise in the Southern.

Velocity of travel.—The velocity with which an anticyclone travels does not appear to have received much attention. However, some data as to the movement of cyclones has already been given, and since the cyclone and the anticyclone are frequently correlative parts of a single great atmospheric disturbance it follows that the two probably travel with substantially the same velocity. The size and frequency of many of the migrating anticyclones are substantially the same as those of the cyclone, while their directions of travel and their paths of maximum frequency, though running farther south, roughly parallel the directions and paths of the latter.

Wind velocity.—The actual velocity of the wind in the different quadrants of an anticyclone and at different elevations is given in the following table by Peppler,[1] based on a large number of observations made during 1903–1908 at Lindenburg, latitude 52° 10′ N., longitude 14° 15′ E. Probably other mid-latitude regions have

[1] Beiträge zur Physik der freien Atmosphäre, 4, p. 95, 1911.

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approximately the same anticyclonic wind velocities. This, however, is not certain, nor is there at hand sufficient data to determine this question.

Anticyclonic wind velocity in meters per second and (miles per hour).

Altitude.	Surface 122 m.	500 m.	1,000 m.	1,500 m.	2,000 m.	2,500 m.	3,000 m.	3,500 m.	4,000 m.
South quadrant:									
Winter	4.43	8.48	8.82	8.68	8.60	8.92	9.71	10.14	10.97
	(9.9)	(19.0)	(19.7)	(19.4)	(19.2)	(19.9)	(21.7)	(22.7)	(24.5)
Summer	3.92	6.19	6.25	6.36	6.17	5.97	6.19	7.08	7.83
	(8.7)	(13.9)	(14.0)	(14.2)	(13.8)	(13.3)	(13.9)	(15.9)	(17.5)
Year	4.16	7.32	7.52	7.51	7.38	7.44	7.94	8.60	9.39
	(9.3)	(16.4)	(16.8)	(16.8)	(16.5)	(16.7)	(17.8)	(19.2)	(21.0)
West quadrant:									
Winter	8.93	7.60	7.19	7.35	7.23	7.21	7.57	7.75	8.11
	(8.8)	(17.0)	(16.1)	(16.4)	(16.2)	(16.1)	(16.9)	(17.3)	(17.9)
Summer	3.39	5.26	5.41	5.18	5.28	5.39	5.20	4.74	5.04
	(7.6)	(11.8)	(12.1)	(11.6)	(11.8)	(12.1)	(11.6)	(10.6)	(11.3)
Year	3.74	6.51	6.38	6.35	6.34	6.38	6.46	6.32	6.65
	(8.4)	(14.5)	(14.3)	(14.2)	(14.2)	(14.3)	(14.4)	(14.1)	(14.9)
North quadrant:									
Winter	4.21	9.69	9.54	9.78	10.19	10.69	11.59	12.29	14.43
	(9.4)	(21.7)	(21.4)	(21.9)	(22.8)	(23.9)	(25.9)	(27.5)	(32.3)
Summer	4.05	7.01	7.68	8.41	8.85	9.51	10.04	10.68	11.45
	(9.0)	(15.7)	(17.2)	(18.8)	(19.8)	(21.3)	(22.5)	(23.9)	(25.6)
Year	4.13	8.35	8.61	9.09	9.51	10.09	10.80	11.47	12.92
	(9.3)	(18.7)	(19.2)	(20.4)	(21.3)	(22.6)	(24.2)	(25.6)	(28.9)
East quadrant:									
Winter	4.29	8.24	8.83	9.56	10.92	12.44	13.52	14.02	15.68
	(9.6)	(18.4)	(19.8)	(21.4)	(24.4)	(27.8)	(30.2)	(31.3)	(35.1)
Summer	3.92	5.88	6.42	6.55	6.98	7.54	7.31	7.83	8.28
	(8.7)	(13.2)	(14.3)	(14.6)	(15.6)	(16.9)	(16.3)	(17.5)	(18.5)
Year	4.06	7.01	7.57	8.00	8.89	9.93	10.35	10.86	11.91
	(9.1)	(15.7)	(16.9)	(17.9)	(19.9)	(22.2)	(23.2)	(24.3)	(26.6)

SECONDARY WINDS.

Although in greater or less measure all winds are interdependent, only a relatively small number obviously are generated and maintained by other and coexisting winds. Among these are eddy winds, foehn or chinook winds, and, presumably, the winds of the tornado.

Eddies.—Wherever the wind blows across a steep-sided hill or mountain, eddies are likely to be formed, especially on the lee side. In such cases the direction of the surface wind is approximately opposite to that of the general or prevailing wind, with a calm between them.

For the practical purpose of the weather forcaster, wind eddies have but little significance, except in one important particular—he must disregard all reports of wind direction obtained at places where eddies are likely to prevail.

Foehn, chinook.—The foehn, or chinook as it generally is called in North America, is a warm, dry wind blowing down a mountain side and over the valleys and plains beyond. It differs from the typical drainage wind in being warm, level for level, and not cold, as is the latter, in comparison with the air of surrounding regions.

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Any system of winds, whether of trade, cyclonic, or other origin, extending to or near to the surface and blowing more or less normally across a mountain ridge, is necessarily accompanied by up-currents, dynamically cooled, on the windward side and down-currents, adiabatically heated, on the lee side, except along the under portions of such eddies as may be produced, where the directions and consequent temperature changes are just the reverse.

From a consideration of all attendant facts and conditions the following statements are justified:

1. Foehns occur at all seasons.
2. The humidity of the foehn is always low.
3. The rise in temperature is greatest when the original vertical temperature gradient is least. Hence, greatest, other things being equal, (*a*) when the upper air is warmest, that is, when there has been precipitation to the windward; (*b*) when the surface air is coldest, that is, when there has been free night radiation (clear skies) on the lee side; and (*c*) during winter, when the vertical temperature gradient through the first several hundred meters may be only 4° C., say, per kilometer, instead of the usual 7° to 8° C. of summer.

Since foehn winds often are swift and the heating rapid, it follows that the most pronounced of them are quite likely to be accompanied also by frequent but irregular convections, and, therefore, strong gusts, swirls, and general turbulence. Under favorable conditions a foehn may even develop a secondary low, the primary, of course, being on the same side of the mountain.

Tornado.—The tornado,[1] in which the air travels in approximate circles, as its name implies, is well nigh peculiar to the United States east of the Rocky Mountains. It is not equally distributed over even this area, occurring rarely in the Alleghenies, seldom along the Gulf and Atlantic coasts, frequently in central and northern Alabama, Georgia, and South Carolina, Ohio, Indiana, Illinois, and southern Michigan, and most frequently in Missouri, Kansas, and Iowa.

The tornado develops usually in the southeast quadrant of an area of low pressure, in which the horizontal temperature gradients are pronounced, and the relative humidity is moderately high.

The season of most frequent occurence is spring and early summer; in fact, during winter tornadoes are unknown, except occasionally near the Gulf and in other warm sections. The time of most frequent occurrence is 3 to 5 p. m. While it is a local phenomenon, the conditions favorable to its genesis are much more extensive, so

[1] For detailed discussion see Finley, Tornadoes, New York, 1887; and Ferrel, A Popular Treatise of the Winds, New York, 1889.

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that a number of tornadoes may develop, even close together, in connection with a single cyclone.

The diameter of the tornado averages only about 1,000 feet (305 meters); the length of its path varies from 100 yards to, possibly, 300 miles (100 meters to 500 kilometers); its direction of travel is nearly always northeast; its rate of travel, though differing greatly, averages roughly 25 miles per hour (11 meters per second), thus passing a given point in half a minute or less; while its winds, always counterclockwise, are the swiftest known, estimated at 100 to 500 miles per hour (45 to 225 meters per second). It is therefore by far the smallest, briefest, and severest of all storms. Essentially, it is a phenomenon of the middle atmosphere. In its genesis clouds whirl around a central core with great velocity and turmoil, while beneath, a funnel-shaped cloud develops, usually tapering off to a long pendant spout that may or may not extend to the earth. Wherever it does reach the surface it produces a deafening roar and practically everything in its immediate narrow path that can be blown down or torn to pieces is destroyed, though generally but little damage is done on either side. On the other hand, wherever it it does not come to the surface its passage produces but little or no effect.

Cause.—From the characteristics of the tornado and from the meteorological conditions that normally accompany it, it appears that its origin must be purely mechanical. Thus its rotation obviously is derived essentially from that of the cyclone in which it occurs, since it is always in the same sense, counterclockwise, however small its diameter, and never clockwise, as is often the case with large dust whirls when formed in still air. But how is the rapid rotation started? From the directions of the V-shaped isobars, when the latter are observed, it is clear that at a kilometer or so above the surface there must be neighboring winds whose directions are approximately opposite—adjacent and, of course, more or less intermingling and overrunning countercurrents. Hence, under these conditions, the inflow that feeds any strong upcurrent, such as always exists just in front of a thunderstorm, must occasionally bring these countercurrents so close together as necessarily to produce a violent whirl.

Here, too, as in so many other cases of atmospheric motion, the law of the conservation of areas, or the constancy of the product of radius of curvature by linear velocity, obtains, except as modified by friction and viscosity. Hence, as the radii of curvature of the opposing currents may at first be comparatively large, but relatively small after being strongly deflected by convection, it follows that the wind velocity within the whirl, in which both the countercurrents are taking part, may be very great. This rotation, however, does not check the upcurrent, hence that convection which, as explained

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above, is essential to the rotation is maintained, and therefore the rising currents are brought in spirally with increasing angular and linear velocity as the axis of spin is approached. Each filament, so to speak, of the spirally rising air viscously drags along its under and slower neighbors, thereby bringing them nearer the axis and increasing their velocity. In this manner the whole of the rising column is set whirling with greater or less velocity. Around the axis of rotation the pressure obviously is reduced in proportion to the centrifugal tendency, the temperature correspondingly lowered, and therefore a cloud spout often formed.

Wherever the inflow of the surface air is greatly checked, or its course so altered by a deflecting hill or other obstacle as greatly to decrease the spin, there the tornado must lift. It may, however, retain its full vigor in the unaffected upper air and soon reach the surface again.

Why essentially peculiar to the United States.—Since the tornado rarely occurs in violent form except in that portion of the United States which is east of the Rocky Mountains, it follows that the combination of meteorological conditions essential to its genesis seldom obtains in other parts of the world. This combination appears to be very simple—only a vigorous convection between strong neighboring countercurrents. Hence, since vertical convection, as indicated by thunderstorms, is common enough in most parts of the world, it follows that the other factor, namely, strong countercurrents, is the distinctly American phenomenon. That such currents should often occur east of the Rocky Mountains is obvious from the position and trend of these mountains themselves and the location of the Gulf of Mexico. No other similar combination of mountain and ocean wind controls exists, and therefore no other place has in all respects the same kinds, frequencies, and intensities of storms.

Waterspouts.—Only its well-established name requires that the waterspout shall be specifically mentioned, since mechanically it does not differ essentially from the tornado, however greatly the two may differ in extent and violence.

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CHAPTER III.

WEATHER FORECASTING, PRELIMINARY STATEMENT.

By ALFRED J. HENRY, *Professor of Meteorology.*

Basis of forecasts	69	Pressure and temperature change charts	72
Cyclones, geographic origin of	70	Terminology	74
Forecasting from synoptic charts	70	Types of isobars	75
The cyclone or LOW	71		

PRELIMINARY STATEMENT.

Basis of forecasts.—After an experience of many years, the forecasters of the Weather Bureau continue to make all forecasts of every character as to future weather conditions solely upon the basis of synoptic weather maps. Such maps give a graphic presentation or picture of the meteorological conditions prevailing for the moment throughout extensive regions of the earth's surface. It is desirable, indeed, that information be available, if possible, for an entire circumpolar hemisphere. Weather maps of the Northern Hemisphere, for example, show the general conditions and the essential features of the circulation of the whole circumpolar atmosphere. Such charts seemingly constitute not only a sound logical and scientific basis for definite, specific, and exact weather forecasts, but, perhaps, the only scientific basis.

By the continuous use and study of daily synoptic weather maps meteorologists generally recognize in the expressions that follow the two fundamentals of modern weather forecasting. These are (1) weather travels; (2) the character of the weather is in general largely determined by the atmospheric pressure distribution. The aim of the forecaster is, therefore, first of all, to determine the type of pressure distribution at hand and to form a mental picture of the future movement and the modifications it is likely to undergo in advancing into regions differing in some respects from its original environment.

It is necessary to fix with considerable accuracy the position of the dominating pressure control 24 or 36 hours hence, since a difference of a few degrees of azimuth may mean snow rather than rain and

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"backing" instead of "veering" winds. Once the location of the pressure controls is fixed, it is a comparatively easy matter to fill in the weather appropriate to the several districts in the line of advance of the storm.

Geographic origin of cyclones.—It is the experience of Weather Bureau forecasters that relatively few cyclones originate in the United States proper, or, more specifically, within the field of observation. The latter includes Alaska and the southern part of the British possessions in North America, the United States proper, and at certain seasons the Greater and Lesser Antilles of the Tropics. The majority of cyclones of seeming local origin appear, nevertheless, either to have existed in the regions far beyond the field of observations or to have originated possibly over the Pacific Ocean itself.

Prof. C. Abbe in the Monthly Weather Review, **23**, page 129, discussing the international weather maps of the Northern Hemisphere, states that these maps clearly demonstrate that—

> in general areas of high pressure and areas of low pressure that first appear in the northwestern corner of the daily weather map do not, properly speaking, originate either in Alberta or British Columbia but are portions of HIGHS and LOWS that circulate between latitudes 40° and 70°. These HIGHS and LOWS are so connected together that sometimes they may be treated as interacting cyclones and anticyclones, while at other times they are interacting troughs and crests of waves, and again they may be considered as a minor episode, like the whirlpool in a rapid stream of water. The international maps show, moreover, that when an area of low pressure or a cyclonic system of winds approaches the coast of British Columbia and Alaska it is generally moving from southwest toward northeast, and that soon afterwards an area of low pressure has developed south and east of the original center, viz, in Alberta and Saskatchewan on the east slope of the Rocky Mountains. Several days are required for this process by which a storm dies away on the western slope and a new one develops on the eastern slope.

Forecasting from synoptic charts.—The forecaster has before him on the synoptic weather map certain observational facts which, although mostly expressed numerically, are rather easily translated into a mental picture of the existing weather in different parts of the country; he has, moreover, auxiliary charts which give expression not only to the actual temperatures and pressures at the moment of observation, but also to the *changes* that have taken place in those elements during the preceding 12 and 24 hours. The state of the sky, whether there is much or little cloudiness and the kind of cloud present, is also available, on a separate auxiliary chart.

The general effect of the whole creates in the mind of the experienced forecaster much the same sort of impression as that produced on the solitary observer who has only the aspect of the visible horizon and a few local signs to enable him to sense the coming weather a few hours in advance.

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The cyclone, or low.[1]—The word cyclone was coined by Piddington in 1848 to represent a portion of the atmosphere characterized by low pressure at its center, in consequence of which the winds in the Northern Hemisphere tend to blow toward the center and follow incurving spirals in a direction contrary to the movement of the hands of a watch when laid on a table face upward; and in the reverse direction in the southern hemisphere. The whole system of incurving winds about a center of low pressure has a motion of translation from place to place, in the United States from west to east, or from southwest to northeast.

The term cyclone in the United States is unfortunately confused with that of the tornado, although the terms represent entirely separate and distinct phenomena.

The term anticyclone, as might be inferred, represents a portion of the atmosphere having characteristics the opposite of the cyclone. Pressure in the center is high and it diminishes in all directions. In the Northern Hemisphere the winds flow spirally outward from the center in a clockwise direction; in the Southern Hemisphere these movements are reversed. Further remarks on cyclones and anticyclones will be found in Chapters I and II.

Cyclones and anticyclones are referred to on the daily weather map as "LOWS" and "HIGHS,"[2] respectively, and these terms will be used in this paper as synonyms for those first named.

Figure 16 illustrates a typical LOW, one that is more highly developed than the average, and in figure 17 is given the position of the same LOW 24 hours later. A comparison of these two charts will reveal at once the fundamental fact on which modern weather forecasting is based, viz, that weather travels. The center of the LOW on March 2, 1904, was in Nebraska; 24 hours later it was over the Lower Lake region, having traveled about 1,300 miles in 24 hours. The area affected by the LOW on the morning of the 2d was in an east-west direction, about 1,750 miles; in a north-south direction about 1,250 miles. We may conceive of the LOW as an immense saucer-shaped atmospheric disturbance, extending upward not to exceed 6 or 7 miles, but having a vastly greater horizontal extent, the whole system moving eastward at the rate of about 30 to 40 miles an hour. The rate of movement of this LOW was considerably above the average.

The direction of the wind at selected stations and the state of the sky, whether clear or cloudy, are shown by appropriate symbols on the chart. The changes in the weather incident to the approach and passage of a LOW are fully set forth in any standard treatise on meteorology; hence we may pass directly to other considerations;

[1] See Introductory note, Chapter I.

[2] Terms signifying areas of low pressure and areas of high pressure, respectively.

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viz, the temperature and pressure changes that attend the movements of HIGHS and LOWS across the country.

Pressure and temperature change charts.—Pressure and temperature change charts are merely convenient devices for graphically showing the changes which have occurred in those elements within the 12 or 24 hours immediately preceding the current map. Both sets of changes are made direct from the figures appearing on the "A" or weather chart. The 24-hour pressure changes are the simple differences between the current values and those for 24 hours previous. In the case of the 12-hour pressure changes a small correction is applied to eliminate diurnal variation.

The 12-hour pressure changes, by reason of the fact that they almost invariably precede the center of the LOW *or the* HIGH *in both time and space, have a certain predictive value*, as we shall set forth at some length in a subsequent part of this work.

For the purpose of graphic presentation we have superposed on the 12-hour pressure changes of March 2, 1904, figure 18, the 24-hour temperature changes of the same date. It will be seen that, generally speaking, areas of diminished pressure correspond with areas of increased temperature and vice versa. This correspondence is strikingly exhibited in figure 19, Pressure and Temperature Changes for March 3, 1904.

The first impression upon viewing the two charts will doubtless be that of disappointment, but a little study will enable one to read the maps quite easily. The black lines indicate 12-hour pressure changes and the red lines 24-hour temperature changes. The regions of falling pressure are separated from those of rising pressure by a heavy black line known as the zero line or line of no change, and, similarly, heavy red lines separate regions of falling from those of rising temperature. There is, during the winter season at least, no part of the country in which changes in either pressure or temperature are absent; both elements being in a continual see-saw. The amount of pressure change in hundredths of an inch and the amount of temperature change in degrees is shown by the figures placed near the respective lines. Areas of pressure change are technically known as allobars. The prefix "an"—up—gives anallobar, for an area of rising pressure, and, similarly, the prefix "kat"—down—gives katallobar, for an area of falling pressure (see also p. 79).

In constructing the charts we have omitted, in order to simplify the drawing, lines showing pressure changes of 0.10 inch or less and the lines showing changes of 0.30, 0.50, 0.70, and 0.90 inch, as well as all lines showing temperature changes of less than 10°.

Generally speaking, both temperature and pressure changes advance from west to east, but the temperature changes are much more

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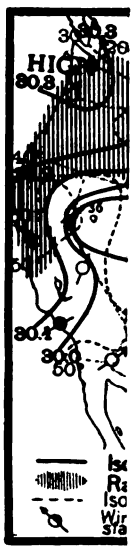

Fig. 16.—Wea
Arrows fly
per hour.

Fig. 17.—Wea

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irregular, both as to extent of territory involved and direction of movement, than the pressure changes.

Falling pressure and rising temperature are closely associated with the movement of LOWS, and, conversely, rising pressure and falling temperature stand in a very close relation to the movement of HIGHS.

Referring, now, to the weather chart for March 2, figure 16, and the pressure and temperature change chart for the same date, figure 18, it is seen that a strong fall in pressure (katallobar) has moved into the lower Missouri Valley and the Plains States, in advance, and to the southeast, of the center of the LOW, and that the temperature has risen over a much greater area, which latter extends roughly from the St. Lawrence Valley to the Middle Rocky Mountain region. It is to be noted also that an independent fall in pressure, amounting to 0.20 inch, overlies the mouth of the St. Lawrence, and that associated therewith is a rise of 10° in temperature. Similarly, a marked rise in temperature has occurred to the southwest of the western katallobar.

Compare, now, figure 18 with figure 19 and note the great change in position that has taken place in the allobars that we have been considering. The anallobar of figure 18 occupying the extreme Northwest has advanced in the ensuing 24 hours to the Plains States and the middle Mississippi Valley; the amplitude of the rise, which on the 2d was 0.40 inch, has increased to double that amount and the area covered is also twice as great as on the day previous. Almost coextensive with this rise in pressure is found a sharp fall in temperature amounting, in the central part of the region involved, to 40° in 24 hours. In Atlantic coast districts rising temperature and falling pressure are found, and on the Pacific coast we note the approach of a fresh katallobar attended by a rise in temperature to the southeast.

In regard to the occurrence of precipitation, it is here merely pointed out that LOWS are generally attended by cloudiness and precipitation and that, on the other hand, HIGHS are associated with clear, dry weather. This subject will be further discussed later in this work.

The shaded areas on figures 16 and 17—the weather charts for March 2 and 3, 1904, respectively—show the regions where precipitation occurred in the 24 hours that ended at 8 a. m. of the respective dates. Comparing these two figures, it is readily seen that areas of precipitation move across the country with the speed of the LOW itself.

Figure 17 serves the purpose of showing not only the 24-hour movement of the LOW, but also the characteristics of a well-defined HIGH. The HIGH and the LOW, or the cyclone and the anticyclone,

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may be considered as a sort of meteorological couple, each member of which, while it has its own special characteristics, is yet more or less dependent upon the action of the other member. Compare, for example, the position and magnitude of the north Pacific coast HIGH on figure 16 with its position and magnitude—and by magnitude is meant its geographic extent—on figure 17. It is seen at once that its magnitude has been vastly increased and that its central pressure has increased from 30.3 to 30.7 inches. At the same time there has been a marked lowering of the temperature along its southeastern front approaching what is technically known as a cold wave—see figure 19.

This brief survey illustrates in a very general way one line of map study which, to become effective, must be extended to hundreds of maps belonging to each type of meteorological disturbance.

It is proposed, in what follows, to develop the subject from a general rather than a local standpoint; that is to say, an effort will be made to point out the weather relations that are associated with the several isobaric formations, their geographic position with respect to each other, their characteristics, and, finally, the special phenomena of cold waves, frosts, storm winds, fog, snow, sleet and ice storms, thunderstorms, etc., will be discussed.

TERMINOLOGY.

It is of much importance that writers on meteorological subjects adhere to a standard terminology, especially in deliberate composition. In the haste that attends the preparation of the daily synopses for the weather maps there is some excuse for defects of terminology, although clearness and exactness, avoiding profuseness and unnecessary attention to minor details, should be the aim of all. Especially should the forecaster be consistent. Thus it is hardly advisable to say "LOW" to-day, "area of low pressure" to-morrow, and "depression" the next day, and "disturbance" the next; all terms referring to one and the same phenomenon. The word "cyclone," as defined in a preceding chapter, has the sanction of good usage and is in all respects a proper term. Unfortunately, its use on the daily weather maps is inadvisable, owing to the fact that in some parts of the country the term is confused in the popular mind with that of tornado, an entirely different phenomenon. The terms barometric maximum, barometric minimum, low-pressure system, high-pressure system, are not objectionable and might well be used as synonyms for the more formal terms, cyclones and anticyclones.

The standard classification of the form of the isobars by Abercromby will be repeated, since this classification has not hitherto been published for the information of Weather Bureau employees.

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Accepting as standard the fundamental shapes as outlined by Abercromby and repeated by others, there is still, it seems, a need of further qualifying terms to describe more accurately the characteristics of individual HIGHS and LOWS. Short and appropriate terms are needed to indicate differences in the temperature conditions which exist in a HIGH, for example; also the differences between a HIGH that is just formed and one that has existed for several days and is consequently at a later stage in its development. The matter was considered as of sufficient importance to warrant the publication of a glossary of words and phrases having a more or less technical meaning that have been used throughout the work. (See the end of the volume.) The board urges upon employees of the bureau who may have occasion to write the importance of uniformity and of adhering to a standard system of nomenclature.

The seven fundamental types of isobars.—1. The cyclone: an area of low pressure bounded by circular or oval isobars.

2. The secondary: a small, circular depression of the barometer, or a loop in an isobar, subsidiary to the foregoing.

3. The V-shaped depression; an area of low pressure, bounded by V-shaped isobars; something like a secondary but differing from it in many important particulars.

4. The anticyclone: an area of high pressure, bounded by circular or oval isobars.

5. Wedge-shaped isobars: an area of high pressure, bounded by isobars convergent to a point, like a wedge.

6. Straight isobars: a barometric slope, down which the isobars lie in nearly parallel lines.

7. The Col[1] or neck of low pressure, lying between two adjacent anticyclones.

The saddle.—Since uniformity of usage with respect to the term "saddle" is sometimes lacking, we reproduce in figure 20 a typical example of the pressure distribution so named. Following is a recent definition of the term, which, it may be noted, agrees with the original definition of Abercromby for the "Col":

> In the saddle-shaped depression of the pressure between two neighboring regions of high pressure the pressure is generally pretty equally distributed, the gradients are trifling, the winds weak, the weather calm and more or less dull or cloudy. In summer the pressure saddle is more frequently the seat of local thunderstorms, which are repeated as long as this distribution of pressure lasts. It is the best breeding place for summer-afternoon thunderstorms.[2]

[1] This term has been replaced in German by Sattel. Bigelow uses the English equivalent "Saddle," but in general that term has not come into use in English.

[2] J. Hann, Lehrb. der Met., 1st ed. p. 593.

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In the succeeding chapter the predictive value of 12-hour pressure changes (allobars) is rather fully discussed. Since the most probable

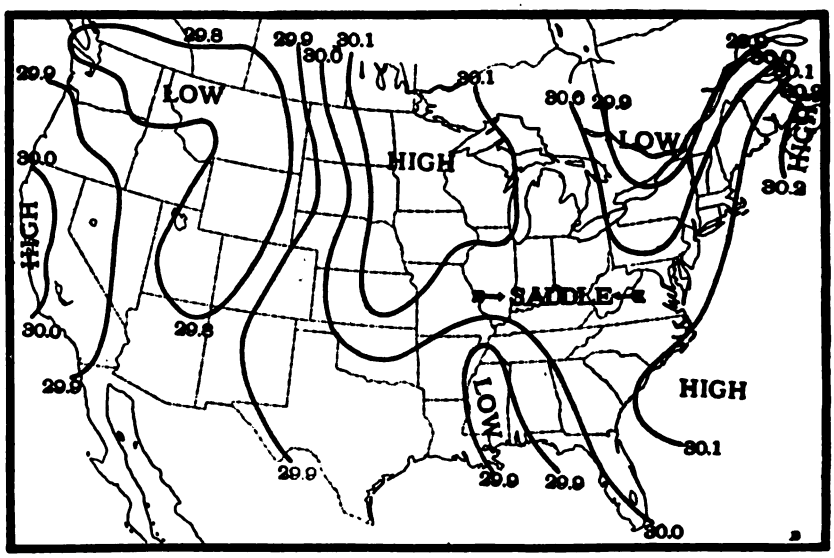

FIG. 20.—Pressure distribution June 14, 1900, illustrating the "saddle" formation.

course of the HIGHS and LOWS is roughly indicated by the allobars, a study of them is of the first importance.

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CHAPTER IV.

AUXILIARY PRESSURE-CHANGE CHARTS.

By ALFRED J. HENRY, Professor of Meteorology.

Auxiliary pressure-change chart	77	Origin of anallobars	82
Diurnal pressure fluctuations	77	Relation of anallobars to temperature-forecasts	82
Irregular pressure fluctuations	78	HIGHS and anallobars	86
Nomenclature	79	Precepts from anallobars	88
The barometric tendency	79	Precepts from katallobars	88
Uncertainty in interpretation	80		
Position of allobars with respect to centers of HIGHS and LOWS	81		

AUXILIARY PRESSURE-CHANGE CHART.

In the beginning of the forecast work in the United States 45 years ago, auxiliary charts of pressure change, temperature change, clouds, and humidity were prepared thrice daily. Since that time the temperature and pressure-change charts alone have continued in constant use in their original form. The cloud chart, after being discontinued for a time, has again been revived; the humidity chart was long ago discontinued.

Not all forecasters set the same value upon the temperature-change chart, but it can be truly said that uniformly they appraise the pressure-change chart at a high value.

While this last-named chart has been prepared constantly for forty-odd years, comparatively little has been written concerning the significance of pressure changes in the art of weather forecasting.[1]

Diurnal or periodic pressure fluctuations.—The diurnal-pressure fluctuations play only an unimportant rôle in forecasting. Because of their small magnitude in the temperate zones and the fact that in the cold season they are frequently obscured by the much greater nonperiodic fluctuations, the influence of the diurnal fluctuations is rarely apparent on the pressure-change chart.

[1] Beginning with August, 1915, the isobars have been entered upon the pressure-change charts, thus adding greatly to their value and making it much easier to correlate pressure changes with the centers of high and low pressure, respectively, than was possible prior to that date.—Editor.

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Practically the only application of the diurnal fluctuations to weather forecasting is in the Subtropics and the Tropics where a suppression or an interruption of the diurnal period is significant of the development of a disturbance. In Chapter V, LOWS and HIGHS, another application of its use will be pointed out. In summer the presence of well-marked diurnal fluctuations in temperate latitudes may be tentatively accepted as an indication of continued rainless weather.

The nonperiodic or irregular fluctuations of pressure.—The nonperiodic pressure fluctuations are so intimately connected with the changes in the weather that a thorough knowledge of them must be considered as one of the essentials of forecasting from synoptic charts. Foul—in the sense of rainy—weather is generally associated with falling pressure and fair weather with rising pressure. It is convenient to think of nonperiodic fluctuations as beginning with a fall of the barometer to a low point which may be termed the "trough" of the fluctuation and its immediate rise to a relatively high level which may be termed the "crest" of the fluctuation. The sequence is therefore trough—crest, trough—crest, etc., repeated indefinitely throughout the year.

Some years since the writer made a compilation of the number of nonperiodic pressure fluctuations occurring in a 10-year period for selected stations on the Pacific coast, the Mississippi Valley, and the Atlantic coast.

It was found that the number of fluctuations was quite uniform for all parts of the country, as is shown by the table below:

Nonperiodic pressure fluctuations in the 10 years 1895–1904.

Station.	Average annual number.	Average interval between fluctuations, in days.
PACIFIC COAST:		
Portland, Oreg.	93	3.9
San Diego, Cal.	86	4.2
ATLANTIC COAST:		
Eastport, Me.	95	3.8
Key West, Fla.	75	4.9
MISSISSIPPI VALLEY:		
St. Paul, Minn.	95	3.8
St. Louis, Mo.	89	4.1
New Orleans, La.	84	4.3

The small differences between the number of irregular fluctuations in the north and in the south, respectively, are perhaps suggestive of the idea that such fluctuations are of much wider extent geographically than the HIGHS and the LOWS with which they are associated.

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A pressure-change chart is simply a convenient device for showing the amount and the geographic distribution of the irregular pressure fluctuations considered in the preceding paragraph, and it supplies also two important desiderata to the forecaster, viz: (1) The amount of the change to lower or to higher pressure, as the case may be, and (2) the geographic position of the areas of greatest change with reference to the path of the LOW or the HIGH. For illustrations of pressure change charts, see figures 35, 36, and 37 of Chapter V.

Nomenclature.—Is it obvious that in order to facilitate discussion of the appearance and movement of areas of falling and areas of rising pressure a single word be provided to identify them.

This need has been anticipated by Dr. N. Ekholm, of the Swedish meteorological office, in a paper entitled, "Das Wetter während der ersten Hälfte, Juni, 1911."[1]

Ekholm proposes and uses in the sense given the following terms:

"Allobar": An area of pressure change.

"Anallobar": An area over which pressure has risen.

"Katallobar": An area over which pressure has fallen.

These expressions will be used henceforth in this discussion in the sense stated and with the further understanding that the region of maximum change will be referred to as the center of the allobar, and that it is this region of maximum change that is plotted as the path of the allobars in the charts which follow. In passing, it should be remembered that pressure change charts do not show whether the barometer is stationary, falling, or rising at the time of observation.

To supply this information, European countries, through the International Meteorological Committee, at its tenth meeting, Rome, 1913, adopted the following:

The barometric tendency, deduced from the barograph records, shall be included in the morning international telegrams. The barometric tendency is explained as the change of the barometer in the three hours preceding the hour of observation. The barometric tendency for telegraph purposes may be characterized in nine different ways: (0) Steady; (1) unsteady; (2) rising continuously; (3) falling continuously; (4) falling at first, now rising; (5) steady at first, now rising; (6) steady at first, now falling; (7) fall checked, now nearly steady or rising; (8) rise checked, now steady or falling; (9) crochet d'orage, gewitter nase, line squall.

While the barometric tendency is not included in weather telegrams sent to the United States Weather Bureau, the value of the so-called two-hour changes is recognized, and they are telegraphed from selected stations. At these stations whenever the barometer rises or falls by as much as 0.04 inch (1.02 millimeters) within the

[1] Conseil permanent international pour l'exploration de la mer publication de circonstance No. 64, Copenhague, 1913, p. 15.

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two hours immediately preceding an observation, that fact is included in the weather telegram. On the Pacific coast a change as small as 0.02 inch (0.51 millimeter) is reported.

How allobars are formed is still one of the unsolved problems of atmospheric circulation. In a general way, high surface temperatures and low barometric pressures and low surface temperatures and high barometric pressures are closely associated, but whether they stand in the relation of cause and effect or whether both are the result of some common cause is still not definitely known.

Katallobars are clearly not dependent on, or caused by, a rise in surface temperature. In general, the surface temperatures in a katallobar are relatively higher than in the surrounding adjacent regions, but the increase in temperature usually follows rather than precedes the fall in pressure.

Uncertainty in interpretation.—It is very generally recognized that the auxiliary chart of pressure changes is the most important

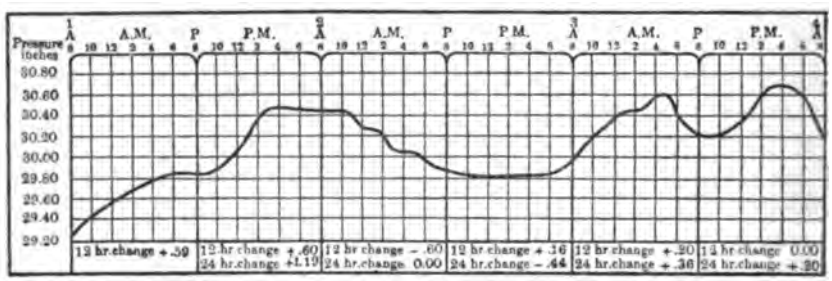

FIG. 21.—Idealized barograph curve.

source of information, aside from the weather chart itself, that is available to the forecaster. There is, however, one source of uncertainty in the application of the data afforded by this chart that it is desirable to point out, viz: The ratio of the 12-hour to the 24-hour change is not always a dependable datum. Many forecasters compare the rate of fall of pressure in the second 12 hours of the 24 with the rate of fall in the 24-hour period, and if the rate of fall in the second 12 hours shows an increase over the 24-hour rate the inference is drawn that the intensity of the LOW is increasing. Such an inference may be correct, provided pressure has been continuously falling during the whole of the 24 hours, but the uncertainty arises from the fact that the pressure in the first 12-hour period may have been rising instead of falling. A comparison of the 12-hour fall with the 24-hour fall will give in the latter case simply the algebraic sum of two quantities, one positive and the other negative, and that result is meaningless so far as forecasting is concerned. The idealized diagram below will show the possibility of confusion. Thus, on the

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p. m. of the 3d the 12-hour pressure change would be plus 20, whereas the barometer at and for several hours before the hour of observation had been falling. On the a. m. chart of the 4th the computed change, 0.00, is far different from the actual change.

Another word of caution is necessary regarding the importance to be attached to the irregular pressure oscillations, the amount of which varies greatly with latitude, being probably twice as great along the northern boundary of the United States as along the southern boundary. The result of this is that the beginner is apt to assign, unconsciously, too great a value to changes along the northern boundary and too small a value to changes in extreme southern latitudes of the United States; moreover, katallobars that progress southeastward across the Plateau and Rocky Mountain regions are continually advancing into lower latitudes where normally the amplitude of the nonperiodic changes decreases. Frequently the pressure fall in a katallobar which moves from, say, Montana to the Gulf of Mexico, decreases to one-third of its original value by the time it reaches the Gulf coast. This fact does not necessarily mean a diminution of the energy of the accompanying LOW.

Having in mind the need of caution, as above indicated, it still appears that the pressure change charts are a valuable asset of the forecaster.

Position of allobars with respect to centers of highs and lows.— In a general way katallobars in winter appear a little south of east and on the right of the path of LOWS moving over the northern circuit. Lack of observations north of this path may make this fact more apparent than real. On the other hand, the fact that surface temperatures on the right of the northern circuit are higher than on the left may be a contributing, if not the principal cause of katallobars appearing on the right of the path of the LOW.

Lows moving northeastward from the Southern States may have a katallobar on either side, indiscriminately.

Anallobars generally appear in the northwest and move to the southeast, and this fact would have a tendency to crowd katallobars always to the southeast.

Sresnewsky,[1] quoted by Dr. Hanzlik in Monthly Weather Review, volume 34, page 205, found "that the center of the cyclone is always to the left of the point of most rapid fall in pressure." Ekholm[2] says, "the path of the cyclone is usually somewhat to the left of the path of the katallobar when the path of the former is from the west toward the east and the general gradient slopes toward the north."

[1] Ueber starke Schwankungen des Luftdruckes im Jahre 1887. Bull. Soc. Imp. Nat. Moscou, 1895, No. 3.

[2] Hann Band der Meteorologischen Zeitschrift, S. 231.

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Origin of anallobars.—Strong anallobars, almost without exception, first appear in the northwest and move east across the Lake Region or southeast over the Plains States; while a third possible course is southwest over southern Idaho, eastern Oregon, Utah, and Nevada. And we may add that in winter anallobars from the northwest are frequently forerunners of a cold wave. As the writer has previously pointed out—Monthly Weather Review, 36: 53—anallobars that advance from the Pacific are not associated with so great a lowering of the temperature as are those from the northwest.

Relation of anallobars to temperature forecasts.—A strong anallobar is not probable, except when a way for it has been prepared by the occurrence of a preceding katallobar. The practical application of this statement is found in making temperature forecasts, especially in the cold season. It is generally safe to assume that the fall in temperature will be roughly in proportion to the previous fall in pressure over the region under consideration, although there are exceptions to the rule. The application of this idea is found mostly in the South, and especially in Florida, in the cold season. Thus it was long a precept in the forecast division that unless a fall in pressure passed over Florida in which the pressure sank to at least 30 inches there would not be a damaging freeze in that State. Further investigation, however, shows that that limit for the pressure is too low. Frosts and freezing temperatures have been known in which the antecedent pressures were not below 30.10 inches, and on December 21, 1901, the temperature at Tampa sank to 24°, with an antecedent pressure not below 30.20 inches. The LOW preceding the temperature minimum was not at any time fully developed. It was prevented from taking the usual course by a well-defined HIGH that moved eastward across the Middle Atlantic States. Pressure over Florida at the center of the LOW did not fall below 30.20 inches at any time during its passage. The HIGH succeeding it was fully developed, with pressure 30.80 inches in the Dakotas. It moved southeastward to eastern Texas, where, on December 20, 1901, pressure was 30.80 inches; thence it moved northeastward across Tennessee and West Virginia. The trend of the isobars after the HIGH turned toward the northeast was nearly north-south; a direction, as elsewhere noted, that is favorable to the transporting of cold air to lower latitudes. A HIGH, with circular or slightly oval isobars, passing north-northeastward over the track as outlined above, will not, as a rule, produce much lowering of temperature over Florida, since the winds will be northeast and the weather probably cloudy. Another case of frost in Florida without low antecedent pressures occurred on January 4, 1896. See chapter on cold waves.

Sometimes it happens that the path of the center of the katallobar is eastward along the northern circuit, but with falling pressure

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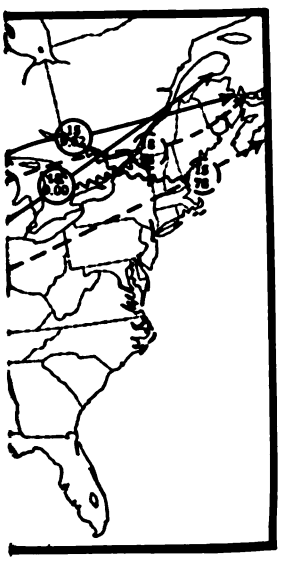

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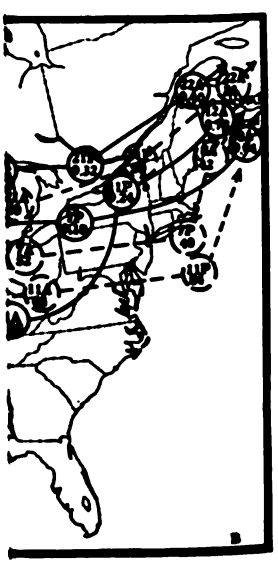

on of Katallobar on January

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extending far to the southward, particularly if the depression is of the V shape, and the apex of the V extends as far south as the Gulf States. In these cases the path of the anallobar may be southward over the Plains States and thence to the east and northeast, describing a long loop to the south of the center of the V and the katallobar.

We now present a number of charts illustrative of the movements of HIGHS and LOWS with their attendant allobaric phenomena.

The first chart of the series, figure 22—see the folder—illustrates the advance across the United States of the front of a katallobar between November 12 and 15, 1911. The forward movement is shown by heavy full lines, which carry the appropriate dates at both ends. In order to show the extent of the katallobar, a heavy broken line has been inserted to represent the line of zero change; thus, the heavy full line dated November 14 represents the front of the katallobar and the heavy broken line of the same date represents the rear at the same instant of time, viz, 8 a. m., seventy-fifth meridian. It is at once seen that the front of the katallobar advances at the rate of 800 to 1,200 miles in 24 hours, and that its greatest east-west dimension may be as much as 1,200 miles or more. The large figures on the chart represent, respectively, the date and the amount of maximum pressure fall in hundredths of an inch in 12 hours, and the figures are placed as near as possible to the exact position of the center of the greatest pressure fall in the katallobar. Figure 23—see the folder—contains the same information for the succeeding three days, the two charts representing the movement of two katallobars from the Pacific to the Atlantic within the six days, November 12 to 18, 1911. The movement was fairly rapid, both crossing the country in the same time—three days. Although these cases were selected because of the simplicity and relative freedom from interference with other allobaric phenomena and, therefore, present the less complex type, there are, nevertheless, evidences of interference on both charts. Thus, on figure 22, the pressure began to rise locally over Alberta a day before the general rise moved in from the Pacific; also, in figure 23, the zero line marking the rear of the katallobar on the 17th is farther to the west over the northeastern Rocky Mountain slope than it was on the 16th. This merely indicates that the temporary rise of the 16th was immediately followed by a fresh fall.

If we consider as one complete cycle the time that elapses between the successive beginnings of falling pressure, then we should say that the cycle in the British Northwest Provinces is frequently a very short one. There is, unfortunately, no means of determining just what phase of the cycle is presented by the twice-daily observations from that region. Some forecasters work on the theory that the phase will be opposite in character within the next 24 hours. Probably in the majority of cases it is, but there are many exceptions.

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In figure 24 (see the folder) we have plotted centers of the two katallobars shown on figures 22 and 23, in connection with the LOWS that followed them; the centers of the LOWS are given in full circles and the centers of the katallobars in broken circles. The dates within the circles will enable one to identify the center of the LOW with its appropriate katallobar. There has been added, as an aid in the identification, a wavy line connecting the two centers. To further simplify the chart the position of the afternoon centers has been omitted; those given are for 8 a. m. seventy-fifth meridian time for the dates specified.

Considering, now, LOW No. 1, figure 24, and its attendant katallobar, it is observed that whereas the former was not manifest as a distinct LOW until the morning of the 13th, over northeastern Wyoming, the associated katallobar was plainly marked 24 hours earlier, off the coast of Washington. Its advance inland and southeastward was exceedingly rapid, passing over 20° of longitude (in latitude about 45°) in 24 hours.

That the center of the 12-hour pressure fall (katallobar) immediately preceding the observation is almost invariably ahead—that is, farther to the eastward than the center of the LOW—is so well established as to require no further argument; and that it is a little south of east with reference to the center of the LOW is the conclusion reached by this brief study.

One of the earliest investigators of the subject, Sresnewsky, quoted by Dr. Hanzlik in Monthly Weather Review, volume 34, page 205, concludes that the center of the LOW is always to the left of the point of most rapid fall of pressure.

The conclusion mentioned above agrees with what we have found for the United States when the direction of movement is from the west to east along the northern circuit; but LOWS that pass from the southern to the northern circuit may have the greatest fall in pressure directly in the line of or slightly to one or the other side of the path of the LOW.

Returning now to figure No. 24, and examining the track of LOW No. 2, we note that it appeared on the North Pacific coast on November 13, 1911. At that time pressure had fallen over somewhat more than the western third of the United States. (See the front of the minimum pressure fall, fig. 22.) Note also that there were three independent centers of maximum pressure fall within one vast area, viz, in N. lat. 40°, W. long. 100°; N. lat. 40°, W. long. 115°; and finally, on the Pacific coast in the neighborhood of San Francisco. The minimum in W. long. 100° moved eastward to the Atlantic, but the remaining two apparently dissipated over the plateau.

Nevertheless, LOW No. 2 advanced to northeastern Colorado before it became associated with a katallobar. The latter crossed to the left

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ry 9, 1903.

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side of the path of the LOW on the 16th and back to the right side on the 17th.

In figure 25 are presented the paths of three LOWS and their attendant katallobars. In this and the subsequent charts, figures 28–31, both the morning and the evening positions of centers of LOWS and katallobars are shown. Low No. 1 of figure 25 is the path of an Alberta LOW, January 5, 1903, that dips only slightly to the southward in passing across the United States. Katallobar No. 1, which accompanies it, follows a slightly different path until the evening of the 6th, when both LOW and katallobar are close together in southern Minnesota; after that date the latter is a little in advance and to the southeast of the LOW.

Low No. 2 of figure 25 is an Arizona LOW that moved first to the southeast and then to the northeast, reaching the Gulf of St. Lawrence on January 12, 1903. Two katallobars attend this LOW in the beginning; they unite in Ohio on the a. m. map of January 11.

Low No. 3 of figure 25 is also of the Alberta group. It crosses the path of its katallobar twice, but in the latter part of its course remains on the right-hand side.

Figure 26 contains the paths of three LOWS and their attendant katallobars. Low No. 1, January 6, 1898, belongs to the Alberta group. Its katallobar pursues a southeasterly course to the neighborhood of Omaha, Nebr., at a very considerable distance from the LOW; thence it turns northeast and evidently joins the LOW over upper Michigan, continuing thence in company with it to the Canadian Maritime Provinces. This figure also illustrates the tendency to subdivision of katallobars.

Low No. 2, figure 26, is an Arizona or South Pacific LOW that moved southeastward to the Texas coast near the mouth of the Rio Grande; thence northeastward to the Gulf of St. Lawrence. The katallobar in connection with this LOW was not well defined, as is usually the case with LOWS in the semiarid regions of the United States. On the morning of the 17th the katallobar was in the vicinity of Great Salt Lake. On the evening map, 12 hours later, three weak katallobars appear—one in southern California, the second in southern New Mexico, and the third at the mouth of the Rio Grande. So far as forecasting is concerned, all of these may be disregarded, except the last. The movement of that katallobar across the semiarid region of the Southwest can not be traced. We have therefore plotted a fresh katallobar as originating over the West Gulf and appearing on the p. m. map of January 17, 1898.

It may be noticed that the path of this katallobar and the LOW, after leaving the Texas coast, coincide quite closely until Lake Michigan is reached, on the 20th. There is then an apparent wide divergence, since the center of the katallobar on the afternoon of the

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20th is off the New England coast, while the center of the LOW at the corresponding hour was over Georgian Bay. This is explained by reference to the original pressure chart, which shows that while the pressure fall was greatest, —0.60 inch, off the New England coast, the fall extended oval-shaped northwestward to Georgian Bay, where it was about —0.40 inch.

Low No. 3, figure 26, is an April storm that apparently originated over southwestern Nevada on April 10, 1906, moved eastward to Colorado, and thence northeastward to Minnesota, where it again altered its course, crossing the Great Lakes and passing down the St. Lawrence Valley. Here again the katallobar pursued a tortuous course, appearing on the morning of the 10th at San Francisco, 12 hours later in southeastern Idaho, and 24 hours later in western Nebraska, where a division seems to have occurred. The second center, which has been plotted as No. 3, appears in the Texas Panhandle.

These two sections pursued a separate course until the p. m. of the 12th, when they united in Iowa and moved thence as a single unit to extreme eastern Lake Superior, where it seemed to halt for 12 hours, being ahead and to the northeast of the LOW. The latter also halted for a corresponding period and then, on the 14th, moved eastward with great speed, as did also the katallobar. This correspondence in movement of the phenomena, while showing that undoubtedly an intimate relation exists, is not of any predictive value, since the movements are practically synchronous.

HIGHS AND ANALLOBARS.

Figure 27 contains the track of a single HIGH, that of January 22, 1905, the two anallobars that attended it, and the track of the LOW of January 23, 1905, that developed over Manitoba immediately to the eastward of the HIGH above mentioned, together with the katallobar that was associated with the LOW.

In order to aid in distinguishing the several phenomena here portrayed the tracks of the HIGH and its associated anallobars are given in red. The track of the LOW is given in black. As before, full circles represent centers of either HIGH or LOW, and broken circles the center of either allobaric phenomena.

The HIGH that is portrayed was first observed in Alberta, with maximum pressure of 30.38 inches on the afternoon of the 22d. In 36 hours pressure had risen to 31.10 inches; it continued above 31 inches for 36 hours, and then slowly dissipated over the Southern States. In the beginning this HIGH was associated with an anallobar, No. 1, which soon disappeared. On the day of its disappearance a second anallobar appeared over Saskatchewan, No. 1a of the chart. This

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second anallobar attended the HIGH during its southward movement and disappeared on the 25th, but during its southeastward movement a third anallobar was developed—No. 2 of the chart. This latter evidently came into existence by reason of the prior development of a katallobar 24 hours earlier (see katallobar No. 1, January 23, 1905), thus illustrating the idea that as a rule each katallobar has its corresponding anallobar and that the latter may be reduced in magnitude by yielding a part of itself, so to speak, to the formation of an independent anallobar.

The division of allobaric phenomena, as illustrated on this chart, is a rather common occurrence. It may also be observed that when the anallobar of the 22d disappeared a second one formed a little to the eastward. Whether this would happen elsewhere, as a general rule, we are unable to say. The tendency to subdivision, however, is of wide application. Again, when a LOW seems to stagnate over the Pacific Ocean or west of the Rocky Mountains the probabilities are that a second LOW will develop farther to the eastward.

On figure 28 of the series we show the path of a single HIGH—that of January 10, 1903, and also of the LOW that preceded it on January 9, 1903, thus giving another opportunity to note the relationship between an anallobar and the preceding katallobar.

It may be observed that the movement was inaugurated by the development of a katallobar over southeastern Montana, on January 9; that in this case the centers of the LOW and the katallobar, respectively, practically coincided and held together for 12 hours. On the morning of the 10th they began to diverge, and by 8 p. m. one was central over southern Minnesota and the other in eastern Missouri. It is also interesting to note that the center of the LOW accomplished practically the same southerly direction as did the katallobar, except that the movement was not inaugurated until 12 hours later. After the 11th the movements do not differ greatly.

The LOW under discussion was followed in 24 hours by a moderate HIGH, which took a course to the southeast, reaching Oklahoma by the morning of the 12th; having been preceded 24 hours earlier by anallobar No. 1. The latter turned to the northeast at Amarillo, Tex., because, it would appear, the katallobar and the LOW preceding it had already made the same turn, though in somewhat higher latitudes. It is observed that the center of the anallobar on the afternoon of the 11th is very close to the center of the katallobar 24 hours previous, thus illustrating the rule that a katallobar is generally followed within 12 to 24 hours by an anallobar.

Figure 29 is reproduced to show the pressure conditions which exist simultaneously with the apparent stagnation of a HIGH over Manitoba or in the Great Basin—see the discussion in Chapter V,

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under "Great Basin Highs" and "Reenforced Highs," pages 131 and 132.

Some of the conclusions reached as a result of this examination follow:

CONCLUSIONS.

(1) In the cold season katallobars, as a rule, diminish in magnitude and in the amount of the pressure fall within them, as they gain distance to the east or south; it is the exception that they increase in those particulars, but when they do it is an indication of an increase in the intensity of the accompanying LOW and such increase should not be overlooked under any circumstances. Under conditions when a change to colder weather seems to be impending a weak katallobar may be completely obliterated by an anallobar. The question sometimes arises in the case of a weak katallobar in the southwest as to whether or not it will persist, and whether it should be given any weight in connection with a LOW in the same locality. The answer is that if an anallobar is close by to the northward the latter will prevail.

(2) *Movement of allobars.*—Allobars generally move from west to east, although in common with LOWS at certain seasons of the year they have a southward component which carries them to the Gulf of Mexico. There is a well-marked hiatus in this movement, especially in the case of LOWS and katallobars, when they reach the vicinity of eastern New Mexico and Western Texas. In this locality they frequently appear to have wholly dissipated. It is not safe, however, to relinquish watch on that immediate locality for indications of a fresh development. We have sometimes thought that the original impulse was not sufficient in many cases to carry the phenomena of LOWS and their attendant katallobars across the arid regions of the southwest, and that only those most fully developed in the beginning survive until they reach the Gulf Coast, where there is an ample store of warmth and moisture. It should be remarked, however, that some of the most enduring LOWS with which the forecaster has to do pass from Arizona to Texas and thence northeastward to New England, without any apparent reinforcement.

(3) *Forecasting precepts from katallobars.*—Katallobars are variously interpreted in forecast work, but we believe that there is common agreement upon the following applications, always having in mind the limitations already mentioned and those which may follow:

(1) *Changes in form.*[1]—A change in the form of a katallobar to that of a circle or an ellipse is a positive indication of an increase in

[1] The form of expression here used should not be interpreted to mean that any inherent power to change its form or alter its movement resides within a katallobar, but rather that the latter is to be considered as merely a graphic form of representing the change in pressure that has taken place in the interval of time between the preceding and the current observation.

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energy on the part of the LOW that attends it, if the latter has not already greatly increased.

(2) *When the greatest pressure fall in the 12 hours immediately preceding the observation coincides with the center of the* LOW *at that moment*, that is, when it does not run ahead of the LOW, the latter has already become, or immediately becomes, a severe storm.

(3) Whenever a fall in pressure that has hitherto extended over a considerable superficial area in blanket form quickly concentrates over a much smaller area, generally in the form of a truncated cone, and the fall over this smaller area increases, then the forecaster has to do with a severe storm.

The predictive value of changes in the form of the katallobar described in the preceding paragraph is not always great, since in a

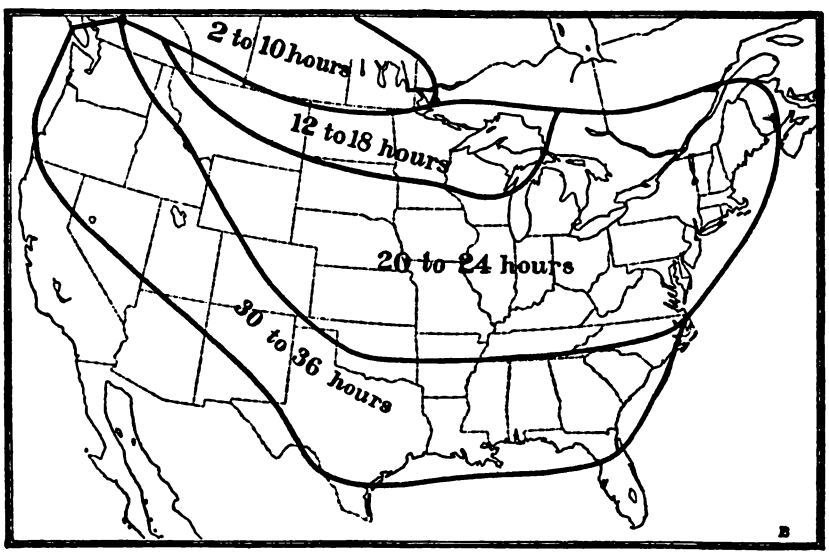

FIG. 30.—Average number of hours Anallobars precede HIGHS.

number of cases the surface isobars become elliptical or circular in form almost coincidently with changes in the form of the katallobar. The apparent change in the latter, however, serves the useful purpose of advising the forecaster that henceforth the attendant LOW will be a severe storm. We lay down the foregoing with considerable confidence.

The 12-hour pressure changes are an important source of information respecting the future course of the HIGH and the LOW, although their indications are by no means absolutely certain and in the warm season they have ordinarily little predictive value. In our opinion anallobars point out roughly the course of the HIGH for the next 24 hours. We present in this connection figure 30, prepared by Mr. W. C. Devereaux, in charge of the Cincinnati office. This chart shows, as

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its title indicates, the number of hours by which anallobars precede the center of HIGHS. It was compiled from October data and may be taken as a good approximation to what happens during other months of the year, except in the warm season.

It is the experience of the writer that when the movement of HIGHS and LOWS is rapid the position of the anallobar in the north approximates the position of the HIGH in the next 12 hours; when, on the other hand, the movement is slow, the interval is most likely to be near 24 hours for the northern half and longer for the southern half of the country. The chart shows that the apparent origin or the first appearance of the majority of anallobars is in the British northwest provinces, and that the movement is southeastward and southward therefrom, or toward the equator.

Katallobars, on the other hand, are less important and less trustworthy in determining the probable course of the LOWS. We consider the HIGH and the LOW as twin members of a system of whirling winds, one member being, in a sense, the complement of the other and inferior to it in independence of movement. We believe the LOW is generally the inferior member; its movement is, therefore, less regular and uniform, and it is subject, moreover, in a greater degree than is the HIGH, to the influence of surface temperature distribution and the occurrence of heavy precipitation in determining its course. These, and probably other influences, about which little is known, often tend to make the course of the LOW erratic as compared with that of the HIGH. As will be mentioned elsewhere, LOWS are occasionally blocked and otherwise retarded by HIGHS and rising pressure. While there are a number of circumstances which seem to indicate a close relation between HIGHS and LOWS and their attendant allobaric phenomena, yet other circumstances arise which suggests that the relation is a loose one. For example, not every anallobar is associated with a HIGH, neither is every katallobar associated with a LOW. Several katallobars may advance into a region occupied by a HIGH of great magnitude without any other visible result than that the HIGH is gradually dissipated. Occasionally the trend of the isobars on the weather map is such that a katallobar may pass across the country without influence upon the shape of the isobaric formations. This is especially true when the isobars have an east-west direction and the katallobar moves in the same direction. Occasionally, too, the fall in pressure, although not sufficient to form a LOW with its cyclonic circulation, is nevertheless sufficient to produce unstable conditions and precipitation, although the form of the isobars may not have been materially altered.

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In this chapter we have discussed the auxiliary-pressure chart made at the central office at Washington and at the district forecast centers. While these charts are not made in detail at stations not forecast centers, the majority of the local forecasters enter pressure and temperature changes either on the "A" chart or separate charts. To the student of forecasting who is not located at a forecast center it is recommended that he make at least the 12-hour pressure changes and study them. In the experience of the writer the 24-hour changes are of minor importance.[1]

[1] Since this was written the 24-hour pressure changes have been omitted from the central office pressure change charts.—Editor.

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CHAPTER V.

LOWS AND HIGHS—GENERAL CONSIDERATIONS.

By ALFRED J. HENRY, Professor of Meteorology.

LOWS:
- Form of ---- 93
- Movement of ---- 94
- Orographic control in the United States ---- 103
- Erratic ---- 105
- Blocked ---- 107
- Intensity, as affected by direction of movement ---- 109
- Precipitation in connection with ---- 111
- Convective rains ---- 113
- Considered by groups ---- 115
- North Pacific ---- 116
- South Pacific ---- 119
- Alberta ---- 120
- Northern Rocky Mountain ---- 121
- Colorado, or middle Rocky Mountain ---- 122

LOWS—Continued.
- Central ---- 122
- Texas ---- 123
- East Gulf ---- 125
- South Atlantic ---- 125

HIGHS:
- Theories of ---- 126
- Continuous rise of pressure in ---- 127
- Increasing pressure at center ---- 130
- Reinforced ---- 131
- Great Basin ---- 132
- Lake region of spring ---- 134
- Hudson Bay ---- 135
- Disintegration of ---- 136
- Precepts from ---- 137

The temperature element in forecastinig ---- 138

The wind element in forecasting ---- 139

LOWS AND HIGHS.

HIGHS and LOWS vary in size, shape, intensity, rate of movement, and other particulars. While it is not possible to enter into minute detail with respect to these particulars, it is thought that some generalizations with regard to the characteristics that seem to be associated with the form of the isobars may be helpful.

Lows, form of isobars in.—Lows that occur most frequently on the U. S. Weather Bureau maps are of the form known as V-depressions, or some modification thereof. Next in order of frequency is the circular or oval form. These two forms represent nearly 70 per cent of the total.

There are two other forms, however, which at once suggest certain attributes that it is well for the beginner to have in mind. For convenience in discussion these two forms will be referred to as "Deep LOWS" and "Crescent-shaped LOWS," respectively.

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The deep LOW is often of considerable magnitude, having circular isobars equally spaced about a center of moderate diameter, say 100 to 200 miles. The pressure throughout the system is unusually low, and in consequence of the circular isobars equally spaced from the center, the pressure gradient is approximately the same on all sides of the system. The deep LOW, therefore, tends to move rather slowly and to diminish in intensity. By reason of the circularity of the isobars, deep LOWS are not attended by HIGHS except at a great distance, and the fall in temperature is not so pronounced as in the case of ordinary LOWS. The important thought in connection with deep LOWS is that of pressure gradient, and the case is cited because it illustrates the importance of noting the barometric gradient in both LOWS and HIGHS. Important deep LOWS are illustrated by the weather maps of February 27–28, 1902, and January 7, 1903. On the first-named date pressure at the center of the LOW was 28.66 inches in Oklahoma. The student is cautioned not to confuse deep LOWS, as above described, with low-pressure systems of small diameter, steep gradients, and low barometer level.

The second group, the crescent-shaped LOWS, appear with some frequency in the Rocky Mountain region and over the Plains States. They may be described as a crescent-shaped, low-pressure system with circular isobars and a cyclonic circulation in both horns of the crescent. The distinguishing feature in addition to the formation described is the presence of a well-defined HIGH on its north or northwest side, which seemingly presses through the middle of the crescent, extinguishing one of the centers of low pressure, and thus crowds the remaining center far to the southeast or east. The important fact in connection with crescent-shaped LOWS is that a severe cold wave occurs in the region occupied by the center of the LOW that has been extinguished. This seems to occur almost automatically. See also the discussion on cold waves, Chapter VI, and weather maps of February 2, 1911–p; April 29, 1907 (p); May 3, 1907a; March 19, 1913; and February 24, 1891.

Movement of lows.—A study of the weather maps of the last 40 years shows that the course of extratropical LOWS in the United States is, roughly speaking, from west to east, with a few modifications that will be briefly mentioned. In winter and spring there is a movement southeastward from the Canadian Northwest and the Pacific Coast States toward the west Gulf States. Many of the LOWS thus moving recurve to the northeast either in Oklahoma, Arkansas, or Texas, while a much smaller number move farther to the eastward before recurving. The general movement east of the Mississippi is to the northeast, passing to sea over New England or the St. Lawrence Valley. The southeastward movement is a seasonal one, being confined to the cold season. In summer the movement of

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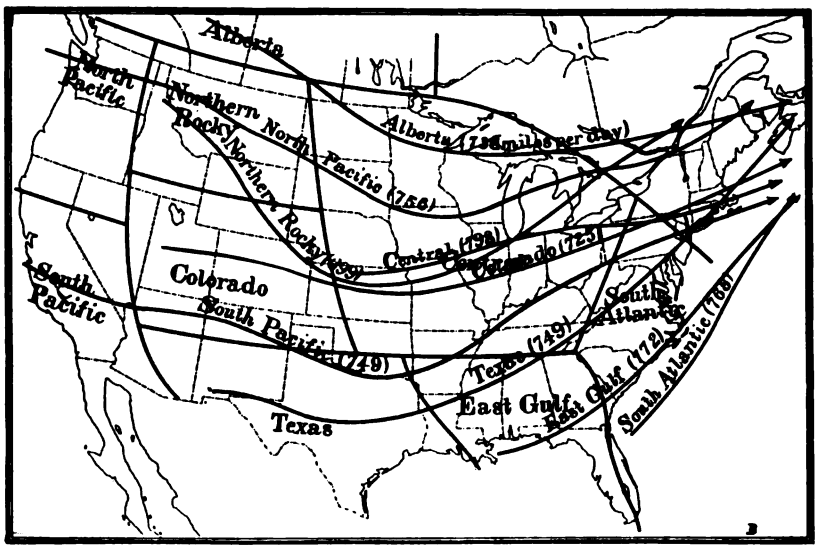

FIG. 31.—Average path of LOWS, January.

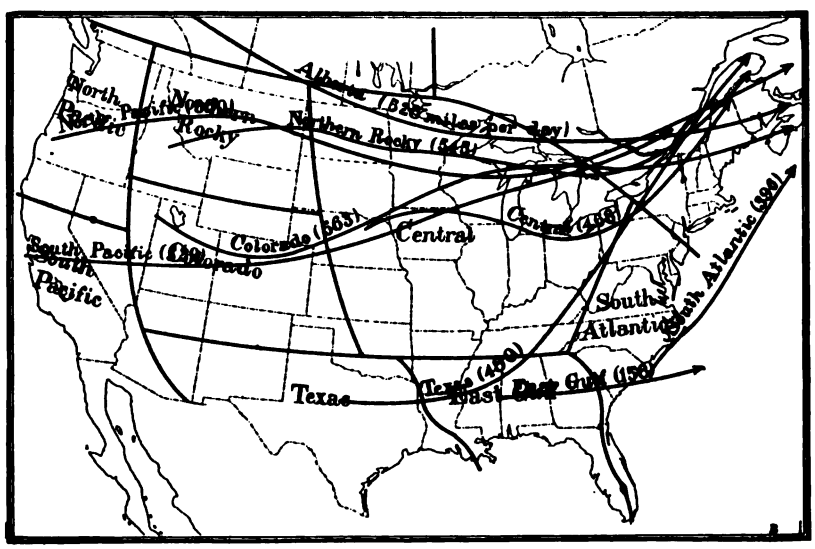

FIG. 32.—Average path of LOWS, July.

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LOWS is mostly eastward, via the northern circuit.[1] Tropical cyclones during this season occasionally enter the Gulf States or Florida and move in a northeasterly direction toward New England. (See figs. 31 and 32, average tracks of LOWS, January and July, respectively.)

Thus, the movement of LOWS seems to coincide with the seasonal direction of the general planetary winds of which they are doubtless a part. Minor local influences may modify the motions, but the dominating characteristics seem to be those of the general circulation.

Certain cloud observations furnish evidence, fragmentary to be sure, that points to a partial control at least of the course of LOWS by the upper winds. In the Monthly Weather Review for June, 1904, Prof. Bigelow discusses under the title, "The Average Monthly Vectors of the General Circulation of the United States," the nephoscope observations made at a few selected stations in the United States during the cloud year 1896–97. He has computed the vectors in velocity and azimuth of the surface winds, as well as of the winds in the lower, middle, and upper cloud levels. The vectors for the upper clouds show, in general, a strong eastward drift, but there is a component directed toward the north at the stations at Kansas City and St. Paul, and in a lesser degree at Abilene. The azimuth of direction of the upper clouds at St. Paul for January, counting from the north as zero, around through the west, is N. 95° W.; February, N. 117° W.; March, N. 158° W.; April, N. 150° W.; May, N. 128° W.; June, N. 113° W. Kansas City, January, N. 95° W.; February, N. 94° W.; March, N. 94° W.; April, N. 104° W.; May, N. 117° W.; June, N. 133° W.

The work of Messrs. Bowie and Weightman published under the title, "Types of Storms in the United States and their Average Movements," gives the average direction of movement of all LOWS, grouped according to place of origin, occurring in any 5-degree square.

We have plotted the direction of LOWS that appeared in the 5-degree square bounded by N. lat. 45–50°, W. long. 95–100° for all months of the year. These plots show unmistakably that for the square in question, which is made up of eastern Nebraska and eastern South Dakota, there is a considerable northward component in the spring months in the motion of LOWS that temporarily occupied that square. The fact that this motion is the same as that of the cirrus clouds in the same region is doubtless more than merely a

[1] "Northern circuit" is the name applied to the storm path which courses easterly from the North Pacific Coast States along the northern boundary, crosses the Great Lakes, and passes down the St. Lawrence Valley. Conversely, "southern circuit" refers to the path of storms which move eastward in lower latitudes to the vicinity of the Gulf of Mexico, thence northeasterly to the Canadian Maritime Provinces.

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coincidence. The curious part of the phenomenon is the fact that the northerly component is much greater in LOWS that originate over the central Rocky Mountain region than in those which have their apparent origin in Alberta.

Further examination of the Bowie-Weightman charts shows that the north component in the square mentioned is also noticeable in the north and south Pacific groups of LOWS, but only after they have crossed the Rocky Mountains. In northern districts the motion of LOWS in May is a little south of east, as during the cold season, and it continues in that direction until midsummer, when it becomes more nearly true east. It seems that after crossing the Rocky Mountains in spring LOWS come under the influence of the summer circulation, viz, from the oceans to the land, and a change in their direction of motion results. It also seems that the mountains form a barrier across which winds from the Gulf of Mexico and the south Atlantic do not pass. All of the southern groups of LOWS have a component directed to the north in all months of the year. The western and northern geographic limits in which this component is effective are naturally reduced somewhat in the cold season, but they expand to the northwest and west in the warm season, as shown by the charts in question.

Generally speaking, there are three principal conditions that indicate the future direction and speed of movement of LOWS, so far as these conditions are indicated by surface observations: (1) The pressure fall in the last 12 hours, (2) the surrounding or local pressure distribution, and (3) the surface temperatures. Of these the last-named is the least important.

The location and the amount of the 12-hour pressure fall generally, but not always, indicate the direction in which the LOW will move; the amount of the fall, however, should be not less than 15 to 30 hundredths of an inch, and the fall should be concentrated in one definite locality. A general fall over a somewhat extended area, amounting to about 0.10 inch, is usually of little avail in indicating the future position of the LOW. High pressure directly in the path of the LOW sometimes seems to be an obstacle to its free movement. We must, however, distinguish between two kinds of HIGHS, which for the want of a better name may be designated as "well-defined" HIGHS and "ill-defined" HIGHS. A well-defined HIGH may be described as one that has existed but a short time and in which the characteristic anticyclonic flow is in active progress. Such HIGHS show more or less definite movement and, to a certain extent, control the wind circulation over the districts temporarily occupied. An ill-defined HIGH may be described as one with little or no movement. The outflow of air is weak or has ceased, and the pressure may be falling. Such a HIGH exercises little, if any, control over the air

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circulation of the district in which it may be located. It behooves the student of forecasting to become familiar with this distinction between the influence of a freshly formed moving HIGH and the same HIGH at a later period in its history.

The writer has found it to be a good precept to consider that *rising pressure and falling temperature anywhere along the northern circuit, either present or prospective, will temporarily bar the northeastward progress of a* LOW *on the same meridian that may be advancing in that direction from the southern to the northern circuit.* This precept is more applicable in the spring months than in autumn, since it seems that in the spring months HIGHS from the interior of the continent with their attendant low temperatures are more effective in withstanding the approach of warm weather and low pressure than at other seasons of the year. Examples of this blocking effect may be seen in the weather maps of February 23, 1914, November 28, 1914, October 14, 1914, and December 4, 1914. See also the discussion on "Erratics" and "Slow Moving Lows," pages 101–105.

No one supposes that any single element of surface conditions available to the forecaster is paramount in determining the direction of movement of LOWS. He must seek the dominating influence from among those which tend to produce motion and those which oppose motion. The belief is justified that LOWS move onward with the general circulation of the atmosphere. This motion, however, is modified by the local conditions of pressure distributions which may exist at the moment. But as these latter are continually changing, the forecaster, in order to succeed, must foresee the changes in the pressure distribution that will occur in time and space, and herein lies the difficulty of making a specific forecast.

Speaking of the movements of LOWS in the British Isles, Shaw and Lempfert say:[1]

> We are as yet unable to identify in the surface observations the conditions which determine the direction or speed of the motion of a barometric minimum.

The conditions under which weather forecasts are made in England are, of course, less favorable than in the United States, yet there are times when the above statement accurately describes the conditions experienced in this country.

Average speed of lows.—It is well known that some LOWS move with much greater speed than others. As the speed of movement is an important factor is forecasting, an endeavor has been made to ascertain the conditions under which the speed of LOWS is accelerated or retarded. Loomis has investigated the subject rather ex-

[1] Life History of Surface Air Currents, p. 24, London, 1906.

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haustively and found the average speed of LOWS for the year to be 28.4 miles per hour.

Von Herrman[1] has also studied the matter. His results agree in the main with the earlier values of Loomis. On the whole, he finds that the average velocities during the three winter months are about 35 miles an hour. Then follows a brief transition period, during which the velocities diminish to about 24 miles an hour, which value is maintained during the five months May to September, inclusive.

Hanzlik[2] has also studied the geographic distribution of fast-moving LOWS. In his summary he says, "But it distinctly appeared that the relation of velocity of cyclones to the gradient was such that higher velocities occurred with weaker gradients in front of the cyclones."

Rapidly moving lows.—There have been selected from the charts of tracks of LOWS in the United States, as published in the Monthly Weather Review for the nine years 1905–1913, the tracks of those whose travel equaled or exceeded 750 miles in 12 hours. In the nine years there were more than 80 cases of movement as above; but on further investigation a few tracks were rejected as having been improperly charted, thus reducing the total number to 77. The table below shows the annual distribution by months. The primary maximum occurs in January, with the primary minimum in late summer and a secondary minimum in February. Hanzlik, using 158 storms, reached practically the same conclusion as to a secondary minimum in February.

Monthly distribution of fast-moving lows, 1905–1913.

January	16
February	11
March	16
April	4
May	3
June	1
July	5
August	2
September	0
October	4
November	5
December	10
Total	77

In order to generalize from these cases a skeleton map was made in each case. A consideration of these maps leads to the conclusion that so far as the surface conditions are concerned the pressure distribution at the time is the most important element to be considered. Under pressure distribution is included both the trend of the isobars and the horizontal pressure gradients. In many cases of rapid move-

[1] Monthly Weather Review 35, p. 169.
[2] Monthly Weather Review 32, p. 358.

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ment the isobars were much elongated in the direction in which the LOW advanced; a very small change in pressure was therefore able to carry it along at a very high speed. The great majority of cases of rapid movement were of this character. It was also found that in certain portions of the United States high velocities are of comparatively frequent occurrence, while in other portions high velocities rarely occur.

On theoretical grounds the eastward drift in the lower strata of the atmosphere in the vicinity of N. lat. 35° should be at a minimum, as compared with more northern districts, and this was found to be generally true as regards the LOWS which happened to be temporarily in that region. A movement from the southern to the northern circuit is frequently made at high speed, but the region of rapid movement is preeminently along the northern boundary from the Canadian Northwest Provinces to the Lake region, and thence down the St. Lawrence Valley. There seems to be in some months a quickening in the speed of LOWS when approaching the Lake region and a retardation while passing across it, though the evidence is not conclusive on either point. That the eastward motion over the northern circuit is more rapid than over the southern, however, there can be no doubt, and to this fact may be ascribed some of the perplexities in forecasting. For example, a barometric minimum that extends north and south over the Plains States generally loses its symmetry when the northern portion reaches the rapid eastward drift of the Lake region and thus forges ahead of the more slowly moving southern portion. The southern portion may or may not persist.

No definite rule can be laid down respecting the manner in which a LOW of this character progresses. It is not to be considered as a mere drifting with the surface winds, but rather, we think, as a wavelike progression to the eastward, in the winds two or three kilometers above the surface, and a more or less rapid filling up of the rear portions by rising pressure, under the influence of anticyclonic winds; thus displacing the system of cyclonic winds farther and farther to the eastward. The eastward movement of the cyclone is doubtless compounded with the direction of the general as well as the surface winds.

In our examination of cases of high velocity we were able to classify them into groups as follows:

BAROMETRIC TROUGHS—THREE CASES CONSIDERED.

(*a*) Troughs in which there are several barometric minima. A very slight change in pressure suffices to displace the center from one end of the trough to the other. This may appear to be a very rapid movement, but should not be so considered. The southern end may

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be obliterated by rising pressure, thus permitting the remaining center of low pressure to progress as an independent storm. (Apr. 10, 1905; Apr. 29, 1907; Jan. 8, 1912; Mar. 26, 1913.)

(*b*) Secondary LOWS sometimes develop in the trough of a primary LOW when the latter has advanced far to the northeast. This happens when the rise in pressure in the rear of the primary is not well marked or is delayed. (See Jan. 10, 1901, and Mar. 14, 1907.)

(*c*) Immature troughs,[1] as when the isobars loop far in advance of the primary over a relatively narrow strip of country. In this narrow space precipitation is generally occurring at the time of observation. Such conditions are a positive indication of the rapid development of the primary LOW in the direction of the loop. These phenomena occur most frequently in the West and Southwest, and the loops extend into the Mississippi Valley. Other places of maximum occurrence are the north Pacific coast region and Alberta, where the direction of the loops is generally southeast.

Example drawn from northern LOWS: February 25, 1907.

Examples drawn from southern LOWS: February 11, 1905; March 11, 1906; and May 3, 1907.

Rapidly moving northern lows.—The isobars of these LOWS may be circular or open to the north; in either case the general trend of the surrounding isobars should be east-west, and the HIGHS should be situated as follows: One over the Great Basin and a second over the Gulf States, or a single, unbroken HIGH in the center of the country may stretch from the Carolinas to Washington. Here and there slight ridges or shoulders of high pressure (the wedge of Abercromby) extend northward from the primary HIGH. These do not check the rapid progress of the northwest LOW. Rapidly moving LOWS are most highly developed in the autumn, when the atmosphere is dry and generally cloudless. They cause very little rain, even along the Great Lakes, but show a rather marked influence on the temperature, owing to the fact that they induce southwest or warm winds over the Ohio Valley and the Lake region.

Examples.—December 3, 1906; January 9, 1907–p[2]; December 24, 1907; November 14, 1908–p; November 17–18, 1908; January 3, 1911; November 22, 1912; December 7, 1912; December 23, 1912–p; January 16, 1913.

Circular lows advancing from the south.—A region from which circular LOWS make rapid progress northeastward is the South Atlantic States, especially if the LOW passes from the continent to the ocean in the vicinity of Cape Hatteras. It will then reach the New Eng-

[1] The term here used is new to the literature of forecasting; the phenomenon described is of rather frequent occurrence, and it is important to grasp the import of the looping of the isobars as described.

[2] The letter p indicates the p. m. chart; absence of subscript letters indicate that an a. m. chart is meant.

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land coast in from 12 to 20 hours, except in those cases where a New England HIGH blocks its path. With a LOW central in Georgia in the cold season, it will generally reach the New England coast within 24 hours.

Circular LOWS also progress rapidly up the Mississippi Valley and thence pass eastward via the Lake region. In deep LOWS of this sort a secondary is apt to develop off the coast of the Middle Atlantic States.

Circular lows between highs.—These move rapidly, especially if the western HIGH is stronger than the eastern. In general, a LOW following a rapidly moving HIGH keeps pace with the HIGH.

Long oval-shaped lows.—As in the case of immature troughs already discussed, the development of LOWS of the above-named shape runs rapidly ahead in the direction of the major axis of the LOW and precipitation occurs some distance ahead of the center of the LOW. A rapid movement may be expected whenever the precipitation occurs far in front of the LOW, and, in general, we may lay down the proposition that the occurrence of precipitation over a region in front of a LOW appears to be among the causes favorable to its rapid movement in that direction.

Slow moving lows.—Perhaps the best evidence of the disintegration of a LOW is to be found in the 12-hour pressure fall. If the area covered by the latter shrinks in size, and the pressure fall diminishes, the LOW is quite apt to lose its distinctive character.

LOWS advancing toward the northeast are sometimes stopped by a HIGH over the Great Lakes or New England. Again, the HIGH may extend from New England westward over the Lake region, with a shoulder to the southwest, forming a sort of crescent.

LOWS advancing from the southwest against a HIGH, as described, are seemingly prevented from reaching New England in the normal course of progression. The LOWS, after reaching the Middle Atlantic States, may remain motionless for a day or so, or they may oscillate slowly back and forth in an east-west direction, apparently showing an indifferent tendency to move in the normal direction. Under such conditions continued cloudy, rainy weather must be forecast until the disappearance of the northern HIGH is indicated by the advance of a katallobar from the west. (See the weather maps of October 13–14, 1914.)

When the drift of the atmosphere is in a normal state, as indicated by the movement of the HIGHS and LOWS, this blocking effect of HIGHS is not much in evidence, but there are times when it is useless to expect a LOW to advance into a HIGH directly in its path.

In the cold season and also in the transition months of spring and autumn there are occasionally short periods when the west-east movement of the atmosphere appears to be temporarily suspended.

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During such periods the movement of LOWS is subject to much uncertainty and there are occasions when it is not possible to foresee definitely the resumption of the normal drift, except for a very short time in advance.

In differentiating LOWS which move rapidly and those which move slowly it is not implied that a LOW is possessed of any attribute that determines its speed of movement. It is believed rather that the speed, as well as the path, of LOWS is determined by the general circulation, subject to modifications due to local pressure distribution. The local pressure influences operate uniformly throughout the year; the general circulation, on the other hand, has a well known seasonal variation, being rapid in winter and slow in summer.

The occasional slackening of speed of the so-called general drift which seems to control the movement of HIGHS and LOWS occurs almost invariably in the transition seasons of spring and autumn, and the cause is to be sought in the readjustment of the general winds, due to the change from summer to winter conditions, and vice versa.

The reduced speed in the movement of LOWS in the warm season is clearly apparent from the averages computed by Loomis and others in which all LOWS were grouped together and a mean result computed. We have sought to determine the visible causes of slow movement from the forecaster's point of view without being particularly concerned in the statistics of actual speed, and have selected from the published tracks of LOWS in the Monthly Weather Review those which had a notably slow movement, roughly 200 miles or less in 12 hours, for the seven years 1903–1909. The number and monthly distribution of slow moving LOWS are exhibited in the table below.

Number of slow-moving lows, 1903–1909.

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Total.
1903	.....	.....	.....	2	3	3	.....	.....	3	2	.....	1	14
1904	.....	.....	.....	2	6	.....	3	1	1	2	2	.....	17
1905	2	4	1	3	1	3	4	3	3	3	3	2	32
1906	1	.....	.....	.....	4	3	2	2	2	2	3	2	21
1907	.....	1	3	3	2	6	2	6	6	2	3	2	36
1908	.....	5	2	4	8	5	5	4	2	5	3	2	45
1909	3	1	2	2	7	6	7	6	3	4	2	3	46
Total	6	11	8	16	31	26	23	22	20	20	16	12	211

GROUPED BY SEASONS.

Winter	29	Spring	55
Summer	71	Autumn	56

From this table it is at once seen that the speed of LOWS varies directly with the strength of the general winds. The strong winds of winter coincide with a minimum number of slow-moving LOWS; that in the transition months of April and May the number of LOWS

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of the slow-moving type is at a maximum, which continues practically until the end of October, when the general winds again become vigorous.

Orographic control of lows in the United States.—The control exerted by the Rocky Mountain and Plateau region on the eastward movement of LOWS is evidently great; not only because of the great irregularities of the surface, which control in a measure surface temperatures, but also, and primarily, it is believed, because of the lack of moisture in the atmosphere between the Sierras and the eastern foothills of the Rocky Mountains. The majority of the slow-moving LOWS of winter are confined to the Plateau region, west of the Rocky Mountains. It is suggested that the characteristic differences between European and American cyclones can be largely traced to topographic influences.

The chief characteristic of LOWS that occupy the Plateau region west of the Rocky Mountains in the cold season is a lack of concentration, so to speak; that is, they are often of very great geographic extent, with one or more separate depressions within a wide spread area of low barometer, and the level of the barometer in these Plateau lows is often relatively high, 29.90 or even 30 inches in winter.

These individual centers of depression shift about from one place to another without any apparent law; sometimes the center is displaced to the westward, even to the coast, by an increase of pressure over the interior.

One important exception should be mentioned, viz, there is a group of LOWS, members of which first appear along the coast of southern California, pass almost directly eastward, crossing the high tablelands of New Mexico, and emerge upon the plains of Texas, whence they pass rapidly northeastward as rather vigorous storms. This group of LOWS has none of the halting movements above described. Another group of rapidly moving LOWS crosses the Rocky Mountains north of Montana, where the divide does not attain to great altitudes. Prof. Abbe, in discussing plateau LOWS, Monthly Weather Review, April, 1894, page 152, says:

> It can scarcely be thought that this rapid southward movement represents either the movement of a whirling system of winds with low pressure, or the movement of the trough of winds with a single wave of low pressure; it is more reasonable to look upon it as the movement of a locus or node of intersection and interference of waves and troughs of pressure that are slowly changing their positions in the atmosphere at some distance above the earth's surface.
>
> The resistances which the atmosphere experiences in its effort to move over the earth's surface may be described as follows: (1) By impinging upon the irregularities of the continents and the waves of the ocean a certain amount of forward motion is annulled and a portion of the atmosphere receives a vertical or even a backward motion, so that the advancing air is mixed with other air moving more sluggishly forward or even backward; as a result the advancing

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air gives up a portion of its momentum to the sluggish air and both combine to move with an intermediate velocity. (2) By the heating of the surface of the earth and the ocean the sluggish-moving lower stratum is made to rise, the more rapidly moving upper stratum descends to take its place, and the resulting intermixed atmosphere moves with an intermediate velocity. As a result of these influences the movement of the middle portion of the atmosphere experiences a retardation that depends upon the amount of vertical convection and that is determined by the roughness of the ground and the intensity of insolation; this amount is, of course, greatest over the continents and in sunlight but least over the ocean and in darkness.

As soon as the isobars of one of the ill-defined plateau LOWS are projected across the mountains upon the plains to the eastward the formation thus established soon assumes the stereotyped circular or oval form, with a system of circulating winds appropriate to a cyclone. The greatest difference between plateau LOWS and those which traverse the great interior valleys, however, is in the moisture supply from the Gulf of Mexico and the south, which is denied the former; owing chiefly to this lack of a supply of warm moist air, it is believed, plateau LOWS exhibit prolonged periods of inactivity. This subject will again be referred to in a discussion of north Pacific LOWS. Suffice it to say that the majority of slow moving LOWS of the winter months are confined to the Plateau region west of the Rocky Mountains.

As the season advances LOWS cross the mountains in northern New Mexico and Colorado. Some of them move northeastward to the Lake region and join the northern circuit, while a considerable number move almost directly eastward, a small percentage passing off the Atlantic coast south of latitude 40°. This group includes the most of the slow-moving LOWS of April and May.

We have examined in detail all of the slow-moving LOWS in the above table from January to May, inclusive, 73 in all. On account of the great labor involved and the short time available, examination of the remainder had to be deferred, but the results for April and May pointed so uniformly to a common cause of the slacking in speed east of the Rocky Mountains that we feel reasonably certain an examination of the remainder would not materially change the conclusion reached, viz, (1) the majority of plateau LOWS in the transition months of April and May pass eastward from the western plateau in the trough form, with shallow barometric minima in the northern and the southern ends of the trough. (2) The northern minimum moves eastward over the northern circuit more rapidly than the southern. (3) It (the northern minimum) is usually closely followed by rising pressure and a HIGH. (4) The arrival of the HIGH in west longitude 95° to 100° is generally so timed as to prevent the southern minimum, which has by this time emerged on the plains, from moving northeastward to the northern circuit; it therefore

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forms a separate disturbance whose normal movement toward the Lake region is seemingly prevented by the HIGH, which has moved in close to the rear of the northern minimum above described. The southern, but now separate, disturbance, must move eastward, south of the normal track and at a speed which is regulated by the movement of the northeastern high, and the latter does not as a rule move rapidly in the spring months. Examples: April 11–15, 1903; May 5–8, 1903; and April 24–27, 1904.

A second cause of the retardation of lows in the spring months is an increase in pressure in the rear of lows that are moving from New England off to sea. It is a common practice among forecasters to ascribe the slacking of speed in a LOW to the presence of a HIGH in its path. To this the writer would add the comment that rising

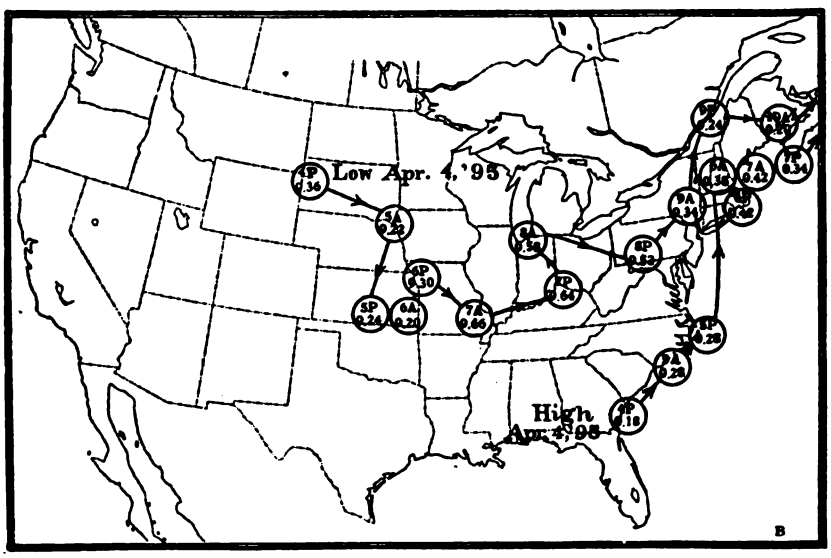

FIG. 33.—Path of slow-moving LOW of April 4, 1895.

pressure in the immediate front of a LOW seems to be more influential in retarding it than a HIGH wherein pressure is falling. Pressure over New England may be as low as 29.50 inches, but if it begins to rise and continues rising, even though the final pressure does not exceed 30 inches, the effect is as great as if the original pressures were considerably above 30 inches. Examples: April 7–9, 1904; April 23–28, 1905; October 15–18, 1911; and others.

Erratics.—Under this term we discuss briefly those cases where the LOW follows an abnormal movement for a short time and then resumes its normal eastward or northeastward drift. The subject is closely allied with that of slow-moving LOWS, to the discussion of which the reader is referred.

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But two cases are considered: First, a LOW that pursued a course to the northwest, viz, from Cairo, Ill., to Keokuk, Iowa, on the night of February 8, 1894; and, second, an April LOW that consumed six days in passing from South Dakota to Maine. The paths of the April LOW and of a HIGH that was the cause of its retardation are shown in figure 33.

The path of the February LOW is shown in figure 34. We also reproduce, as of importance in connection with the February LOW, the auxiliary pressure-change charts of 8 a. m. and 8 p. m., February 8, and 8 a. m., February 9, 1914—figures 35, 36, and 37.

The LOW in question developed over Texas on the afternoon of February 7, 1894. At that time an Alberta LOW occupied the region north of Montana, and pressure was relatively low over the Plains States, between the Texas and the Alberta LOWS. The former moved northeastward to Memphis in 24 hours, central pressure diminishing from 29.64 to 29.28 inches. The isobars are shown in red lines in figures 35, 36, and 37. In the meantime the northern LOW had moved eastward and partly merged with the southern LOW.

The 8 a. m. 12-hour pressure-change chart, figure 35, shows a region of falling pressure extending approximately from the Gulf of Mexico to Manitoba, with the greatest fall over Arkansas. The concentration of the fall in that region marks the southern LOW as the dominating one.

The succeeding weather map (see the isobars on fig. 36) shows the center of lowest pressure at Memphis, Tenn. The normal course from that position is northeastward through the Ohio Valley to New England. Figure 37 shows, however, that the LOW advanced north-northwest, lowest pressure being at Keokuk, Iowa. Its movement thereafter was in accordance with the normal expectancy.

In looking for the cause of the abnormal jog during the night of the 8th–9th, we note that on the p. m. map of the 8th the barometric gradient, as roughly determined by the closeness of the isobars, is least toward the northwest and greatest toward the northeast. An anallobar prominently shown on figure 36 is passing to the eastward north of Lake Superior and the line of zero change in pressure (fig. 37) has given way only slightly to the northeast, thus indicating the temporary domination of rising pressure. These two facts, rising pressure in the normal course of the low and a weak barometric gradient in the rear and to the northwest, seem to indicate that during the period from the afternoon of the 8th until the morning of the 9th the LOW was in a semi-stagnant condition, while slowly readjusting itself to the pressure conditions developed during the preceding 24 hours.

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FIG. 34.—

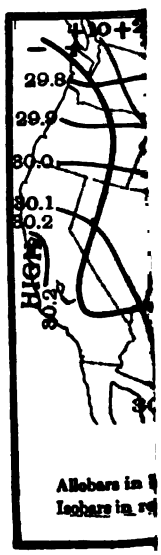

FIG. 35.—

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The second case considered is that of an April LOW, April 4–10, 1895, which was doubtless retarded by a HIGH that passed northeastward from Alabama to New England, central pressure increasing from 30.20 to 30.40 inches, as shown on figure 33. The stagnation of this HIGH over New England, with its increase in pressure, was accompanied by the stagnation of the LOW over eastern Kansas for 36 hours. During the last 12 hours of the 36-hour period pressure at the center of the LOW began to rise, which fact indicated a loss of intensity by the latter. From the 6th to the 8th the movement of the LOW was erratic, and at one time—the night of the 6th—the attendant katallobar almost disappeared. The jog in the path of the LOW on the night of the 7th, when the center was displaced to the northwest, was due to a slight readjustment of the interior pressure, which sometimes takes place within LOWS of great superficial extent, whose free movement is temporarily hindered.

In this case pressure rose slightly in the southern part of the center of the LOW and fell in the northern part, thus displacing the center of low pressure to the northwest, while the general configuration of the LOW as a whole remained practically unchanged.

Mr. Edward H. Bowie has brought to our attention several excellent examples of the blocking effect of HIGHS that build over the Canadian Maritime Provinces. We reproduce, as figure 38, page 121, the weather map of April 18, 1910, illustrating the pressure distribution characteristic of this phenomenon; also Mr. Bowie's notes, made at that time.

The maps, April 18 to 27, 1910, illustrate the blocking of storms by high pressure over the Maritime Provinces. The building of this HIGH seemingly takes place over this region or it may be a southward movement from Labrador. At this season the region under discussion is covered with ice and snow, while the continent to the west is warm, so that the natural conditions are favorable to the continued slow increase of pressure and at the same time the area of rising pressure spreads westward and southward over New England. The condition results in a stagnation of atmospheric conditions generally east of the Rocky Mountains, and any LOWS coming from the west and encountering it are retarded and in marked instances may remain stationary for several days.

It is not safe to assume that a storm subject to retardation from this source will pass off the coast and the weather clear until the pressure falls decidedly in the northeast corner of the map.

Attention is invited to the weak barometric gradients about the center of the LOW of the above-named date, except in an east-west direction. This is a characteristic of "blocked" LOWS. By the morning of the 22d the LOW in question was central off the New England coast and a second LOW overlaid the middle Mississippi Valley. This second LOW, like the first one, was retarded in its eastward progress

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by high pressure over the north Atlantic and the Canadian Maritime Provinces, and it was not until the 28th that it finally passed off to sea.

The kite flights at Mount Weather during the prevalence of the LOWS above mentioned showed that while the LOW is yet far to the westward of that station, a southerly wind sets in, which at the beginning and at the greatest altitudes attained—slightly over 4,000 meters—may be west-southwest. This wind becomes more southerly as the low center approaches the station and eventually shifts to the northwest. There were southwest winds continuously at Mount Weather from April 15 to 21 and again from April 23 to 27, thus indicating a constant supply of southerly winds aloft during the life of the LOW.

During the time above mentioned the pressure over the Canadian Maritime Provinces alternately rose and fell, apparently without reference to the direction of the upper winds at Mount Weather.

This discussion merely emphasizes the control that is exercised on the movement of LOWS by rising pressure, however that is produced. Elsewhere we have touched upon the subject of a rise in the central portion of a HIGH (p. 130). We confess that our grasp of the significance of the phenomena is not so complete as we would like. In the case of the HIGH whose track is shown in Fig. 33, it is to be remarked that the increase in the central pressure from 30.18 on the afternoon of the 4th to 30.42 on the afternoon of the 6th, especially in a HIGH advancing from the *south*, is an exceptional occurrence.

The pressure at the surface must be regarded as the weight of the superincumbent air, and this weight will depend upon the density of the air as well as upon the height of the air column; changes in density can, of course, be brought about by an increase in the height of the air column, as by the inflow of air over the upper portion of the HIGH, or by changes in the air temperature, or humidity, or both.

We have observed a number of cases wherein an increase in pressure in the central region of a HIGH occurred contemporaneously with the diminution in speed of a western LOW, but it is not certain that the phenomena stand in the relation of cause and effect. The impression remains that the underlying causes are both seasonal and geographic, because (1) the phenomenon of increasing pressure in the center of a HIGH is mostly observed late in spring, and (2) it is rarely observed except over New England, the Canadian Maritime Provinces, and a narrow strip westward therefrom to Manitoba. Cases may occur, however, in any month from April to October, but they are rather infrequent outside of the locations mentioned.

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Intensity of lows as affected by direction of movement.—In this discussion an increase in the central pressure of a LOW has been considered as equivalent to a diminution in its intensity, and, conversely, a decrease in the central pressure has been considered as equivalent to an increase in intensity. As a matter of fact these criteria are not complete, but they point in the right direction and therefore can be used without serious error.

Since mean pressure in the Northern Hemisphere diminishes from about N. latitude 30° toward the pole, it may be assumed that central pressure in a LOW advancing northeastward toward the northern circuit must diminish; and, conversely, that central pressure in a LOW whose eastward movement is diverted toward the southeast must increase. The single exception to the last-named case is noted when a second LOW is moving northeastward toward the northern circuit. In this case a western LOW approaching the meridian upon which the southern LOW is located tends to dip southeastward and merge with the southern LOW, with or without an increase in central pressure of the northern LOW.

There has been an understanding among forecasters that LOWS which move to the left of their normal path increase in intensity. In order to put the matter to a short statistical test the two tables below have been constructed. In forming the tables the paths of all LOWS in February for the five years 1910–1914, inclusive, have been considered. Column 1 of each table contains the names of the special groups of LOWS that occurred during February, classed according to origin, as is customary. The first table includes all LOWS whose plotted 24-hour movements departed 5 or more degrees to the right (south) of their normal paths, the 24-hour movements plotted in Monthly Weather Review Supplement No. 1 being considered as the normals. The second column contains the number of 24-hour movements of those LOWS in each group which were attended by a fall in pressure, and the third column contains the mean pressure fall for the whole number of cases. The fourth column contains the number of 24-hour movements of LOWS which were associated with a rise in pressure, and the fifth column contains the mean rise in pressure in hundredths of an inch. The sixth column contains the number of cases of no change, and, finally, the seventh and eighth columns include, respectively, the total number of cases and the total pressure change as deduced from the algebraic sum of the positive and negative changes.

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Central pressure changes in lows that moved 5 or more degrees to the right (south) of the normal path.

[Computed for 24-hour movements. Pressures in hundred of an inch. All values plus unless written minus.]

Lows.	Number of cases.	Mean change in pressure.	Number of cases.	Mean change in pressure.	No change.	Total number of cases.	Algebraic sum of pressure changes.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Alberta	14	−24	12	17	0	26	−1.33
North Pacific	12	−17	17	22	1	30	1.75
South Pacific	1	−18	8	16	0	9	1.14
Northern Rocky Mountain	2	−10	0	.....	0	2	−0.20
Colorado	6	−09	18	09	1	25	1.12
Texas	8	−16	6	09	0	14	0.76
South Atlantic and East Gulf	2	−15	1	02	0	3	−0.28
Total	45	.....	62	.....	2	109	2.96
Mean	.....	.....	.....	.....	.....	.....	0.27

Central pressure changes in lows that moved 5 or more degrees to the left (north) of the normal path.

[Computed for 24-hour movements. All values plus unless written minus.]

Lows.	Number of cases.	Mean change in pressure.	Number of cases.	Mean change in pressure.	No change.	Total number of cases.	Algebraic sum of pressure changes.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Alberta	23	−16	4	09	2	29	−3.35
North Pacific	12	−11	11	13	0	23	0.12
South Pacific	13	−19	3	25	0	16	−1.70
Northern Rocky Mountain	1	−24	1	04	0	2	−0.20
Colorado	18	−25	10	16	2	30	−2.90
Texas	11	−35	2	10	0	13	−3.60
South Atlantic and East Gulf	2	−49	0	.....	0	2	−0.98
Total	80	.....	31	.....	4	115	−1.261
Mean	.....	.....	.....	.....	.....	.....	−0.110

Similarly the second table shows the same information for LOWS which departed 5 degrees or more to the *left* of their normal paths derived in precisely the same manner as above described.

Analyzing the results shown in the two tables we may say that the tendency to a fall in central pressure is most pronounced in LOWS which depart to the *left* of their normal path, especially in those which move from south to north, but it is to be noted that 27 per cent of all cases of movement to the left show an *increase* of pressure instead of a decrease. The results are therefore more or less inconclusive, since any precept to be useful should hold in at least 75 per cent of the cases.

The first table shows that 45 24-hour movements to the right were attended by a fall in pressure, and that 62 cases moving similarly were attended by a rise in pressure; whence it appears that almost as many LOWS that move to the *right* of their normal path

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are attended by a *fall* in pressure as in the case of those which move to the left. The tables show also that the algebraic sum of the pressure changes which attend Alberta LOWS in their march eastward is negative, while on the other hand that of north Pacific LOWS is positive, regardless of whether the divergence is to the left or to the right. Finally, the evidence of the tables is such as to lead to the conclusion that whether a LOW swerves to the right or to the left of its normal path is of limited application as a means of determining whether or not it will increase or diminish in intensity.

PRECIPITATION IN CONNECTION WITH LOWS.

Precipitation occurs in connection with the great majority of low-pressure systems. The notable exceptions are few and as follows:

(1) Shallow LOWS, moving along the northern circuit in autumn yield little or no precipitation until they reach the Lake region and occasionally not then. The absence of precipitation seems to be due to (*a*) the general condition of the atmosphere at that season of the year with respect to moisture, (*b*) the level of the pressure in the depression, and (*c*) the rapidity of movement of the latter. Both rapid movement and relatively high pressure are inimical to precipitation.

(2) A small number of LOWS that move southeastward to the vicinity of Oklahoma yield no precipitation and some of them eventually become extinct. The pressure distribution at the time must be the criterion as to the future of such LOWS.

(3) A small group of LOWS with very low central pressure occasionally appear in the spring and early summer months over the northern Rocky Mountain region, with a tendency to a northward movement. These LOWS rarely give more than widely scattered light rains. In summer they are apt to produce excessively hot weather in the interior valleys as they drift eastward. (See weather maps of July 2–11, 1897.)

In case two, above described—dry LOWS in Oklahoma—the situation is immediately reversed, if a high be placed to the northeast, say, over the lower Missouri Valley, for the reason that such a configuration will induce relatively cool northeast winds over Oklahoma and adjacent regions where previously relatively warm southerly winds had prevailed.

It is reasonable to assume that the warmer southerly winds are underrun by the northeasterly winds, and that the forced ascent thus caused results in precipitation. The general principle involved may be expressed as follows: *When the high is north or northeast of the low, the tendency to unsettled weather and precipitation*

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in the regions between them is at a maximum. There are several corollaries to the above that will appear elsewhere in this work.

Precipitation from the different forms of isobars.[1]—Whether one form of isobars is more productive of precipitation than another is a difficult question to answer. We are inclined to the belief that whether or not precipitation will occur depends largely upon the source of the air that supplies the LOW. East to southeast winds are preeminently the rain winds of the United States. On the Pacific coast the southeast winds are land winds and are probably colder in winter than the westerly winds which flow inland from the Pacific. Owing to the topographic conditions in the Coast States, the southeast winds—the most common rain winds—and the west winds are both mechanically forced to rise, and the rainfall of that country may well be classed as orographic, as has been done by Curtis. In the central and southern Rocky Mountain and Plateau regions the northeast wind is by long odds the rain wind, while the summer rainfall is largely due to local convection. The type of rain map for the Rocky Mountain and Plateau region is low pressure over the southwest, specifically, anywhere over northern Arizona, Nevada, Utah, western Colorado, or northern New Mexico, with a strong high to the northeast. The LOW may pass inland from any one of the northern groups.

In the Mississippi Valley and thence eastward precipitation occurs easily with almost any form of isobar, provided the wind is in the southeast to south. A V-shaped LOW, with the apex of the V extending into the lower Mississippi Valley, is a rather common and very rainy type. Likewise, a long oval, stretching northeast-southwest, or simply a barometric trough extending in the same direction, causes heavy precipitation. Farther north, as in New England, precipitation also occurs with a northeast wind on the southern margin of an extensive HIGH with relatively low temperatures.

The reservation should always be made that at times, as in cases of prolonged drought, all indications of rain drawn from the synoptic charts fail, and in this we recognize the popular saying, doubtless coined long before the day of synoptic charts, "All signs fail in dry weather."

Precipitation as conditioned upon the level of the barometer.—There is no hard and fast relation between the height of the barometer and the occurrence of precipitation. Precipitation in the form of sleet or light snow may begin with pressure as high as 30.5 inches. The amount, however, is generally small. A considerable quantity of rain is not likely to fall with the barometer above 30.2 inches, although a widespread precipitation area, mostly in the form of snow, may be caused by a barometric minimum of 30.2 inches. (See map of Feb. 10, 1914.) Snow seems to occur with higher pressure

[1] See also Prof. Cox's remarks, pp. 300–301.

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than rain, and it often begins with pressure between 30.2 and 30.5 inches. Prof. Cox has fixed a lower limit of the barometer level in those disturbances which cause precipitation in the upper Mississippi Valley (see p. 301). A similar rule can be given for V-shaped depressions that pass over the region about the District of Columbia, viz, that rain is most likely when the barometer sinks below 30 inches.

CONVECTIVE RAINS.

The term "convective" as applied to rains was used by Curtis to designate rains due to a circulation that is primarily vertical. The term as here used is applied to rains in Florida, along the Gulf coast, and in other regions where the local conditions of temperature, wind, and moisture satisfy the requirements of local convective action and, further, because the cyclonic origin of the rains in those regions is not apparent. The student will save valuable time by considering convective rains as being in a different category from cyclonic rains.

There are two districts in which convective rains occur during the warm season. The first of the districts is along the Gulf coast, including the Florida peninsula, and extending back into the interior probably not more than 50 miles, the exact border not being as yet determined. Its east-west length is approximately 700 miles, or from the Atlantic in the neighborhood of Jacksonville, Fla., to about Houston, Tex. The pressure conditions associated with these rains are about as follows:

A HIGH, with pressure 30.15 to 30.20 inches, overlies the southern portion of the middle Atlantic, with an extension over the Florida peninsula, in which pressure is 30.08 to 30.10 inches. Pressure diminishes in a westerly direction to a region of indifferent gradients over southeastern Louisiana. The gradients are for gentle southeast winds along the coast and over the narrow fringe of the interior.

Another and somewhat similar pressure configuration prevails at times in the summer, differing from the one just described in that a wide and shallow trough of low pressure extends from the Gulf of St. Lawrence southwestward via the Ohio Valley to the lower Mississippi Valley. This configuration is associated with local thundershowers throughout the trough and in the interior of the east Gulf States, whereas the convective rains are confined to a coastal strip and Florida. There is little movement in these troughs, consequently a series of several days of unsettled, showery weather may be expected before the weather clears.

The hourly frequency of convective rains in southeastern Louisiana is well shown by Coberly in "The Hourly Frequency of Pre-

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cipitation at New Orleans, La.," Monthly Weather Review, volume 42, page 537. From Mr. Coberly's table we compute the percentage of day rains as compared with night rains at New Orleans, La., as follows:

Day rains:	Per cent.
June	77
July	78
August	84
September	69

Mr. W. P. Stewart, local forecaster at Galveston, Tex., points out in the Monthly Weather Review, volume 41, page 1225, some peculiarities of midsummer showers at Galveston. He says:

> The convectional showers which occur with considerable regularity during the summer months over the mainland near the east Texas coast fall only occasionally on Galveston Island. The reason for this is that the southerly winds usually prevailing when these showers occur have practically the same temperature as the waters of the Gulf of Mexico from which they have just come. They are, therefore, comparatively cool, and have little tendency to rise. After they have passed inland a few miles, however, they become sufficiently warm to induce the convectional ascent that results in local showers. These showers occur, therefore, usually a few miles inland and not on the immediate coast.

The writer is of the opinion that the pressure distribution in the case of the Texas convectional rains is slightly different from that which causes rains along the middle Gulf coast and in Florida in that the level of the barometer in the HIGH is a little greater, probably as much as a tenth of an inch, and the center of the HIGH is more to the westward, nearer the Mississippi Valley, than in the case of the middle Gulf coast rains.

Mr. Howard H. Martin, assistant observer, stationed in Texas, has pointed out in an unpublished manuscript that a rain forecast for northeast Texas can be made when high temperatures in connection with a weak barometric depression prevail over that region and there is probability of opposing winds due to high pressure to the northward.

In the application of this method difficulty is frequently experienced in detecting the barometric minimum and determining the strength of the northern HIGH. Unless opposing winds result the forecast will be a failure.

The second region of convective rains is in the southwestern mountain regions, principally in New Mexico, southern Colorado, and Arizona. The type is well marked in summer but is more highly developed in some seasons than in others.

While we have spoken of these rains as convectional showers, we are not unmindful of the fact that convective action seems to be facilitated or more pronounced, so to speak, in a region of weak

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pressure gradients, particularly in the trough between two distant highs. Forecasting rains in the mountain and plateau regions in summer is a wholly different problem from that of forecasting cyclonic rains in the Mississippi Valley and thence eastward. The relation of pressure distribution to rainfall in the Southwest in summer is somewhat obscure; it appears, however, that rainy periods lasting two, three, or four days are inaugurated by HIGHS *that pass from the Pacific eastward across the northern portion of the Great Basin to Wyoming, western South Dakota, and Nebraska;* whence one portion may continue eastward, while the western end apparently stagnates over the Plains States, northeast of New Mexico and Colorado. The weather maps of July 17–19, 1914, are typical of rain-producing HIGHS in the middle and southern Rocky Mountain region. Pressure is low throughout the summer in southwestern Arizona. The movement of a HIGH eastward as above stated places this semipermanent Arizona LOW and the eastward moving HIGH in the proper relative positions, as indicated in our general statement, to produce precipitation.

As happens along the Gulf coast, and as required by the theory on which convectional ascent is based, the summer rains of the Southwest are a phenomenon of the daytime, although there is a considerable number of cases wherein it is safe to assume that the action inaugurated by the ascent of warm air in the afternoon has continued well into the night.

A compilation of the times of beginnings and endings of precipitation at Santa Fe, N. Mex., altitude 7,013 feet, and at Wagon Wheel Gap, Colo., altitude 9,235 feet, during July and August of the rainy season of 1914 shows the following:

Santa Fe, N. Mex., number of rains beginning between—	
Midnight and 7 a. m.	9
8 a. m. and 6 p. m.	55
6 p. m. and midnight	28
Wagon Wheel Gap., Colo., number of days with rain between—	
Midnight and 7 a. m.	11
7 a. m. and 6 p. m.	52
6 p. m. and midnight	24

CONSIDERATION OF LOWS BY GROUPS.

WESTERN LOWS—NORTH PACIFIC, SOUTH PACIFIC, ALBERTA, NORTHERN ROCKY MOUNTAIN, AND COLORADO OR MIDDLE ROCKY MOUNTAIN LOWS.

In the remainder of this chapter it is proposed to discuss briefly the distinguishing characteristics of the various groups of LOWS that appear on the daily weather maps, classed, as has been customary hitherto, according to the place of their apparent origin. Accordingly we distinguish first the LOWS which pass over the continent from the Pacific; a further distinction in this group is made

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between LOWS which pass inland above latitude 40° N. and those which pass inland south of that parallel. These two groups are known as the north Pacific and south Pacific, respectively. Next in order is an important group known as Alberta LOWS, since they first appear in the Province of that name; and, finally, the northern Rocky Mountain and Colorado or middle Rocky Mountain group. Figures 31 and 32 (ch. V) show the average path of the different groups of LOWS for January and July, respectively. Figure 31 is reproduced from Supplement No. 1, Monthly Weather Review, 1914, and figure 32 was prepared in the forecast division of the central office.

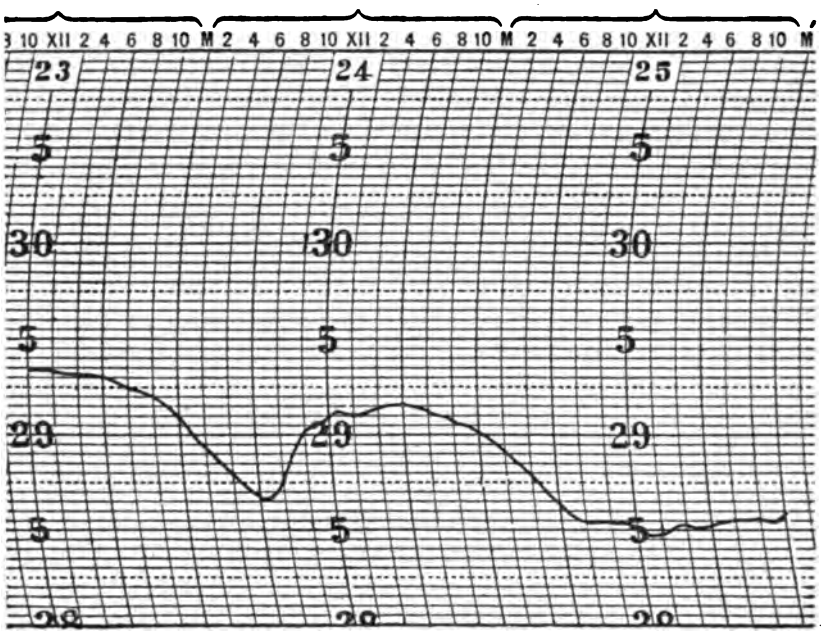

FIG. 39.—Barograph trace, Roseburg, Oreg., January 23–26, 1914.

It is probable that a large proportion of the western LOWS thus grouped originate over the Pacific. Since cable communication has been established between Alaska and the United States, and daily weather reports have been received from that region, it is perceived that the semipermanent oceanic LOW, sometimes referred to as the Aleutian LOW, oscillates back and forth from west of the Aleutian Islands to the Gulf of Alaska, sometimes with a southward extension that reaches to the mouth of the Columbia River, on the North American Continent. We now perceive that the oscillations from ocean to land, and vice versa, of LOWS which approach the Pacific coast (see Monthly Weather Review 23, p. 3) are merely surges of the North Pacific LOW as it alternately advances and retreats.

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The short periods of rising pressure along the Washington and Oregon coasts which elsewhere on the continent would be accepted as tokens of fair weather must be considered merely as minor incidents in the life history of the North Pacific LOW. The key to clearing weather on the Pacific coast, however, is to be found in a uniform and considerable rise in pressure, as much as 0.2 inch or more in 12 hours along the California coast. In order to prevent any misunderstanding as to what is meant by "short periods of rising pressure" we present in the diagram above a copy of the barogram made at Roseburg, Oreg., for the period noon, January 23, to midnight, January 25, 1914. This barogram, figure 39, covers the period when a LOW was approaching the coast. Note, first, a steady fall in the pressure from about noon of the 23d to about 7 a. m. of the 24th. The amount of the fall was about 0.68 inch. *The barometer then began to rise and rose about 0.47 inch by 6 p. m. of the 24th;* it then began to fall and continued falling until some time in the evening of the 25th. In other words, the steady fall in the barometer with the approach of the LOW was suspended for a period of nearly 12 hours and was then resumed. This reversal, which is not uncommon on the Pacific coast, adds greatly to the perplexity of the forecaster.

According to the count of Bowie and Weightman (loc. cit.), north Pacific LOWS form 15 per cent of the grand total of all LOWS. They cross the continent at a rather rapid rate, but a considerable percentage of them becomes extinct before reaching the seventieth meridian of west longitude. For the 10 years ending with 1909, less than 60 per cent of North Pacific storms passed entirely across the continent.

The seasonal variation in both Pacific groups of LOWS is well marked. The maximum frequency is in the winter, while the number of LOWS drops to a very decided minimum in July and August. In this respect they differ from Alberta LOWS, the latter group being at a maximum in summer.

It seems evident that the frequency, especially of north Pacific LOWS, is conditioned upon the depth and geographic position of the north Pacific oceanic LOW. If the latter is fully developed, and occupies a position over the Gulf of Alaska or along the coast of British Columbia, as in January, 1914, then will north Pacific LOWS be at a maximum. The summer minimum in Pacific LOWS is explained on the ground that at that season the temperature contrast between the continent and the ocean is the reverse of that which obtains in winter, and the development of LOWS takes place over the continent rather than over the ocean. The large number of Alberta LOWS in summer is probably due to this fact.

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North Pacific LOWS may move almost due east along the northern circuit, or they may move southeasterly as far as Texas and thence northeasterly to the northern circuit. (See figs. 31 and 32, ch. V.)

The southeasterly movement is confined to the cold months of the year and is probably due to the winter circulation.

During the transition months of April and May, north Pacific LOWS, if they survive crossing the Rocky Mountains, come within the influence of the summer circulation of the interior and generally move toward the Great Lakes. The inability of these LOWS to cross the Mississippi Valley in the month of May is clearly shown in figure 40, which indicates that but 1 of the 10 north Pacific LOWS that appeared in the 5 years ending with 1909 survived and reached the

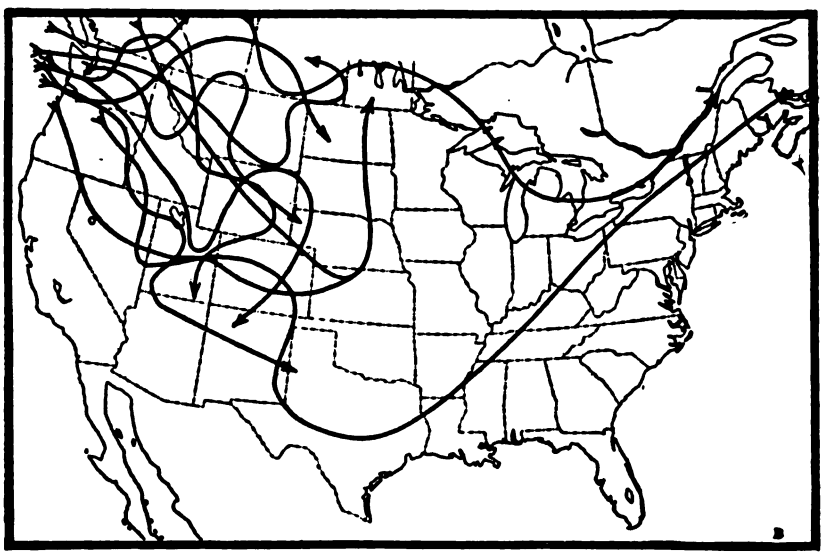

FIG. 40.—Paths of North Pacific LOWS, May, 1905–1909.

Atlantic coast, and but 2 got as far east as the Lake region. A much greater percentage of south Pacific LOWS survives in the spring months and passes east of the Mississippi than is the case with north Pacific LOWS.

When the north Pacific oceanic LOW is the predominating control of the weather we have probably as near an approach to type control for the northern United States as ever happens. However, by reason of the great spreading of north Pacific LOWS after they enter the continent, it would still be difficult to foresee the precise path each LOW would take in order to clearly specify the weather that should prevail in each district. Figure 41 is presented to show the diversity of movement of north Pacific LOWS for January for a period

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of 10 years. The tracks printed in black are for the 5 years, 1900–1904; those printed in red are for the succeeding 5 years, 1905–1909.

South Pacific LOWS do not scatter so much as North Pacific LOWS, but pursue a more uniform eastward course; a greater percentage of them survives until the Atlantic is reached. The months in which they seem to possess the greatest endurance are December and February.

Forecasting from north Pacific coast lows.—A simple and very general rule for forecasting the weather in the Pacific Coast States is "southerly winds bring rain; northerly, fair weather." When the oceanic LOW of the north Pacific projects over the North American Continent that fact is generally indicated by continued low pressure off the mouth of the Straits of Fuca. When such conditions prevail the winds will be southerly and the forecast should be for rain. The real test of the forecaster's skill for Pacific Coast States is shown by his success in forecasts of fair weather. A novice on the Pacific coast would doubtless begin to predict fair weather as soon as the barometer began to rise. As we have already pointed out, a rise in pressure may be merely a brief interruption in the curve of falling pressure. Hence, the necessity of a correct interpretation of the changes in pressure along the coast. The first set of changes from stationary to falling pressure is apt to be merely preliminary, and the forecaster should get special barometric reports, if the case is urgent, or wait until the next set of reports is made, when circumstances warrant. He will then be able to form an idea whether the changes are progressing uniformly and in the original direction.

To determine when an independent LOW will become separated from the ocean LOW and pass over the continent requires the exercise of the best judgment of the forecaster. Falling pressure within the last 12 hours, provided the amount of the fall is at least 0.25 to 0.30 inch, is considered the best indication of inland movement that is available. If the visible LOW is centered along the coast south of the Columbia River it is best to allow 24 hours for a probable northward movement to the Straits of Fuca, entrance to the continent generally being made at that point. The probable course of a north Pacific LOW across the United States in January is almost due eastward along the northern boundary and the Lake region, to the St. Lawrence Valley. (See fig. 31.) In some cases LOWS of this group will move southeastward across the Rocky Mountains in Wyoming and Colorado to the southern Plains States, and thence northeastward to New England; such a course is often indicated by a looping of the isobars southeastward over the Rocky Mountains; also in the position of the HIGHS over the Great Basin or the Canadian-Northwest; remembering that there is a tendency for LOWS to follow the periphery of an adjoining HIGH and to pass

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between HIGHS when the latter are separated by a slight barometric trough.

By reason of topographic conditions, the movement of north Pacific LOWS across the Plateau and Rocky Mountain region is often masked and difficult to follow; in some cases it is almost impossible to locate the true center of the disturbance on the synoptic charts. The precipitation is for the most part confined to the higher altitudes; in the lowlands it is light and infrequent. But there is one type of north Pacific LOW that is clear cut and immediately recognized, viz, that characterized by a strong HIGH central over Montana or the region to the northward of that State, around whose periphery on the south and west sides is found a series of LOWS beginning with one on the Washington coast and ending with one in southwest Colorado, or even on the Plains to the eastward of the mountains. A second characteristic of this pressure distribution is the persistence of the trough form of low pressure that stretches from the Washington coast southeastward to southern Idaho or even farther. The northeastern HIGH is always separated from the low pressure by very strong temperature and pressure gradients. The latter are really due to the fact that a cold wave prevails on the eastern slope of the mountains, but does not extend to the summits. West of the mountains temperatures are relatively high due to an inflow of air from the Pacific. The behavior of the northeastern HIGH depends largely upon the pressure distribution at the moment; it may move eastward along the northern circuit or an offshoot may develop, which later passes southeastward to the Mississippi Valley and thence northeastward; or the original HIGH may settle southward over the Great Basin and cause cold waves in Washington and Oregon and killing frosts in California. (See maps of Jan. 25–27, 1902.)

The detachment of a HIGH toward the east is generally followed by a LOW which forms in the trough between the original HIGH and the one that separates from it and moves eastward.

This type is best developed in February, but cases may occur in any month from November to March. (See the periods beginning Feb. 1, 1899, Jan. 24, 1902, Feb. 5 and 13, 1904, Feb. 1, 1905, Jan. 29, 1907, Jan. 7, 1909, and others.)

Alberta lows.—The Alberta group of LOWS furnishes slightly more than 30 per cent of the total number that appears in the daily weather maps. In the cold season, LOWS that enter the continent north of British Columbia doubtless first appear on the daily weather maps as of origin in the Province of Alberta. In the warm season it is believed that the origin of these LOWS is over the continent rather than the ocean, and that LOWS may originate anywhere in the interior valleys from the Gulf of California northward to the Arctic Circle.

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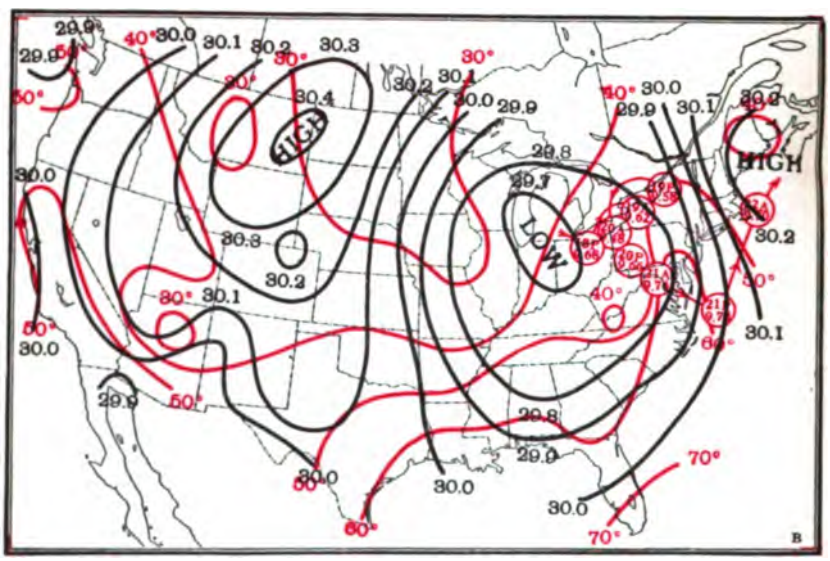

Fig. 38.—Slow-moving Low, April 18, 1910. (Isotherms and path of Low in red.)

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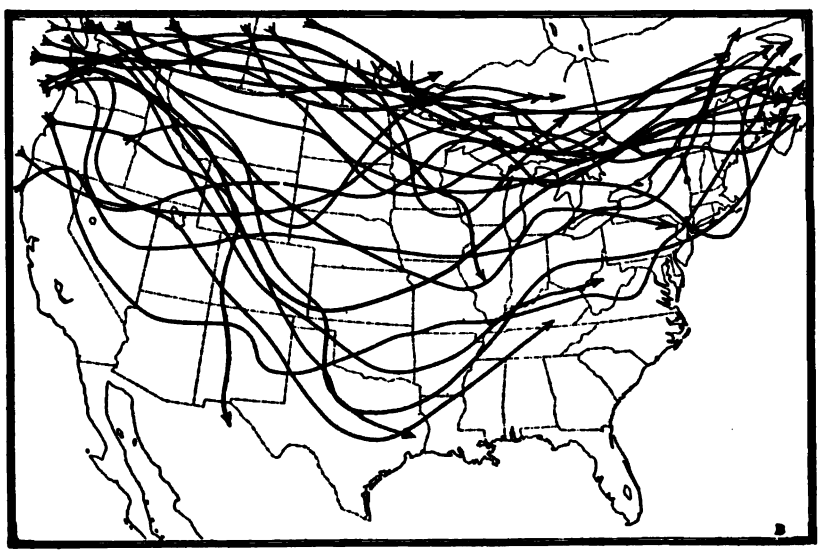

FIG. 41.—Paths of North Pacific LOWS, January, 1900–1909. (1905–1909 in red.)

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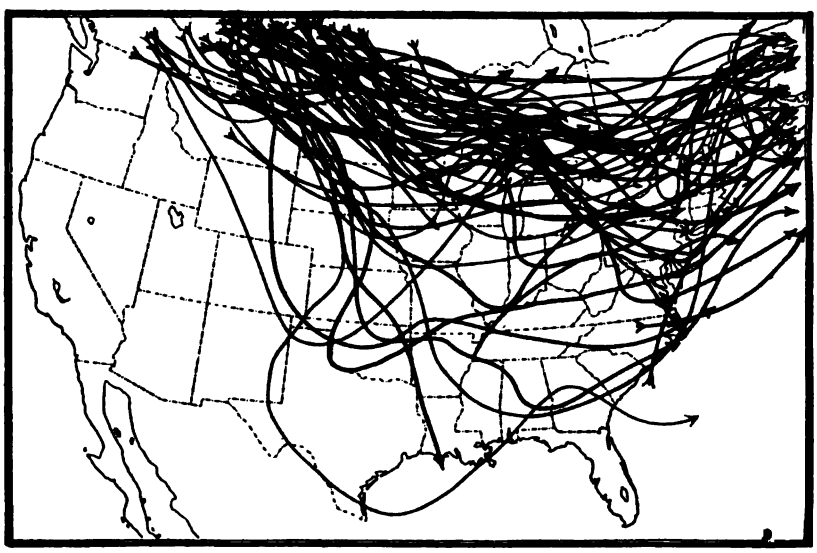

FIG. 42.—Paths of Alberta LOWS, January 1900–1909. (1905–1909 in red.)

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Alberta LOWS are more stable than Pacific LOWS; that is to say, a greater percentage of them reaches the Atlantic. The following comment on north Pacific and Alberta LOWS with reference to their stability is made in Weather Bureau Bulletin A, a Summary of International Observations, Washington, 1893:

> The storms which appear on the Pacific coast north of Washington possess greater vitality than any other class of storm passing over the Northern Hemisphere. Storms of tropical origin are generally short-lived, and those recurving eastward generally dissipate after reaching the middle latitudes.

While a considerable number of them move to the southeastward in the cold months as well as along the northern circuit, the southeastward movement is not so pronounced as in the north Pacific group. Compare figure 41 with figure 42, which show, respectively, the tracks of north Pacific and Alberta LOWS for January for the 10-year period 1900–1909. There is no very striking difference between the paths of the two groups of LOWS.

Forecasting rain and temperature changes attending Alberta lows.—Alberta LOWS are mostly open to the north and the depression of the barometer in many of them is not great. There is always a probability, amounting in the autumn months almost to a certainty, that an Alberta LOW, moving along the northern circuit with lowest pressure above 29.90, will not cause any precipitation of consequence. There is a rough sort of relation between the level of the barometer in the center of the LOW and the probability of precipitation, the probability increasing directly as the level of the barometer sinks. (See Prof. Cox's rule, p. 301.) There is, however, as we have said elsewhere, no hard and fast rule by which one can tell whether or not a LOW passing eastward along the northern circuit will give precipitation, nor, if so, how far south of the track of its center precipitation will extend. In the spring, as pointed out by Prof. Cox, it is not advisable to forecast a rapid movement of Alberta LOWS across the Lake region, when the latter is occupied by a slow-moving HIGH.

Occasionally Alberta or other LOWS moving eastward in the northern circuit, when reaching west longitude about 95°, bend to the southeastward and pass off to sea below latitude 40°. This southward tendency appears to be controlled by the pressure over the Atlantic between Halifax and Bermuda. In any event, if pressure is 29.90 inches or lower at Bermuda, other things being equal, a northern LOW is apt to take a southeastern course from the Lake region toward Chesapeake Bay. (See weather maps of Mar. 3, 1905 (a), Feb. 22, 1908 (a), and Feb. 15, 1914 (a).)

Northern Rocky Mountain lows.—The LOWS of this group are closely related to north Pacific and Alberta LOWS; the main point of difference between them is that they apparently originate farther

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eastward than do north Pacific LOWS. The period of minimum frequency in northern Rocky Mountain LOWS is in the cold months of December, January, February, and March. According to Bowie and Weightman, the maximum occurs in August, with a secondary maximum in May.

Colorado or middle Rocky Mountain lows.—The maximum number of Colorado or middle Rocky Mountain region LOWS occurs in March and April, with a secondary maximum in October and November. While many of them doubtless have their origin in troughs of low pressure that have advanced from the Pacific, and while they bear a rather close relation to Pacific and Alberta LOWS, still they differ in this important particular, viz, that they occur with fairly uniform frequency in all months of the year, whereas Pacific LOWS have a decided minimum in the summer months.

Shallow LOWS that rarely attain any importance are occasionally first noted over the Plateau and Rocky Mountain region, particularly over eastern Colorado. These LOWS are sometimes referred to as "heat" LOWS in the belief that they owe their origin to a mass of air that has become unduly heated from one cause or another.

The fact that Colorado LOWS show their maximum at the transition periods of the year and also a decided turn to the northeast in April and May suggests that their development in the warm season is in some way connected with the general circulation of the atmosphere.

The forecasting of precipitation and temperature changes from Colorado LOWS presents no features differing essentially from those of other LOWS under the same conditions.

The central group.—The central group is composed almost wholly of secondary LOWS that develop in the trough of a primary LOW from the west or northwest, which for one reason or another disintegrates as it approaches the central region of the United States.

These LOWS form about 10 per cent of the total number, and the time of their greatest frequency is in the late spring and late fall months, resembling in this respect Colorado LOWS. They present no especial characteristics which call for comment.

SOUTHERN LOWS.

TEXAS, EAST GULF, SOUTH ATLANTIC LOWS.

In the previous part of this chapter we have considered groups of western LOWS, viz, those which originate in the west and move toward the east. In the present group we will consider those LOWS, whatever their place of origin, that move northeastward from Texas and the Gulf States or advance northward from the region about Florida to the New England coast. As before stated, a certain num-

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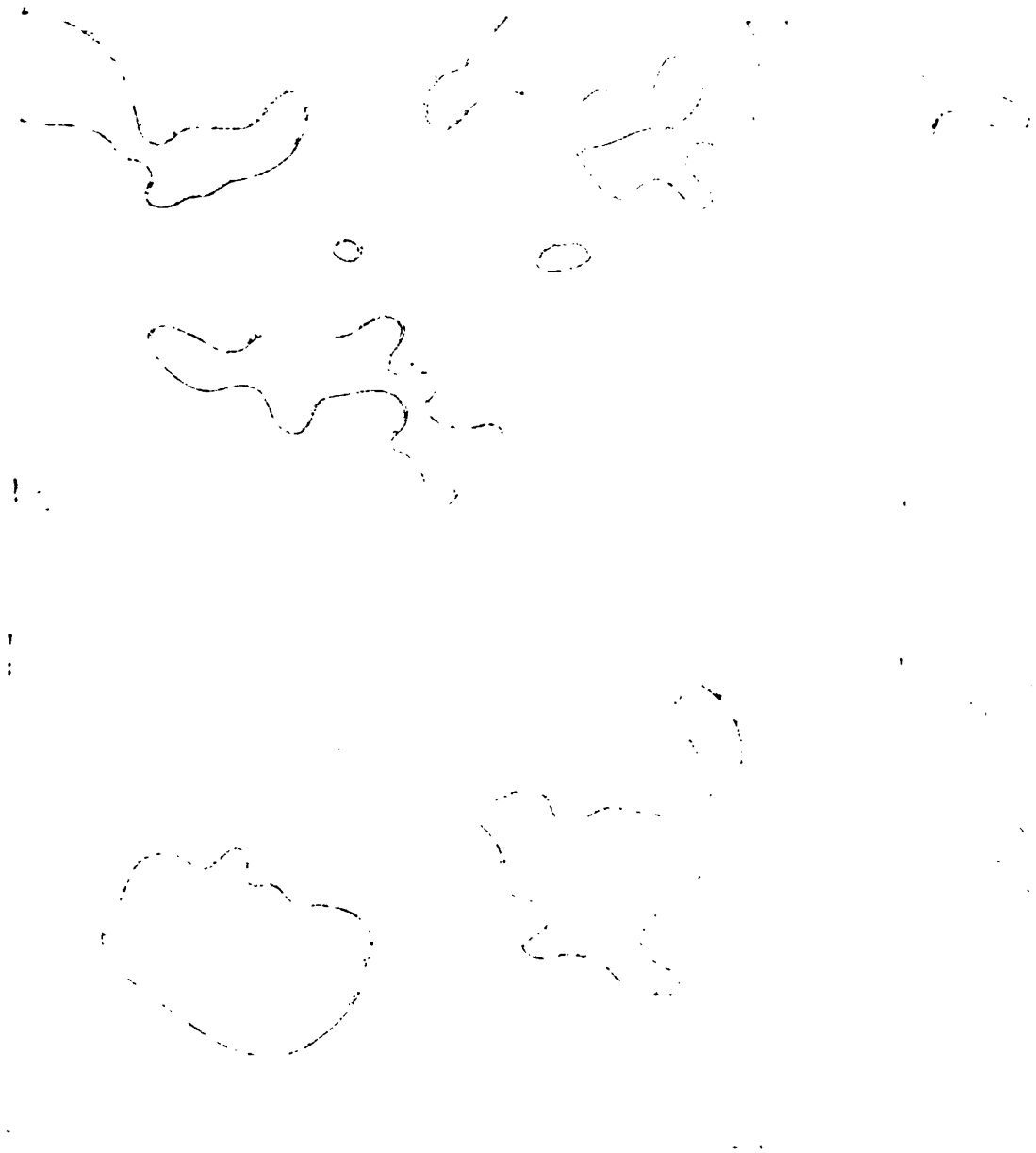

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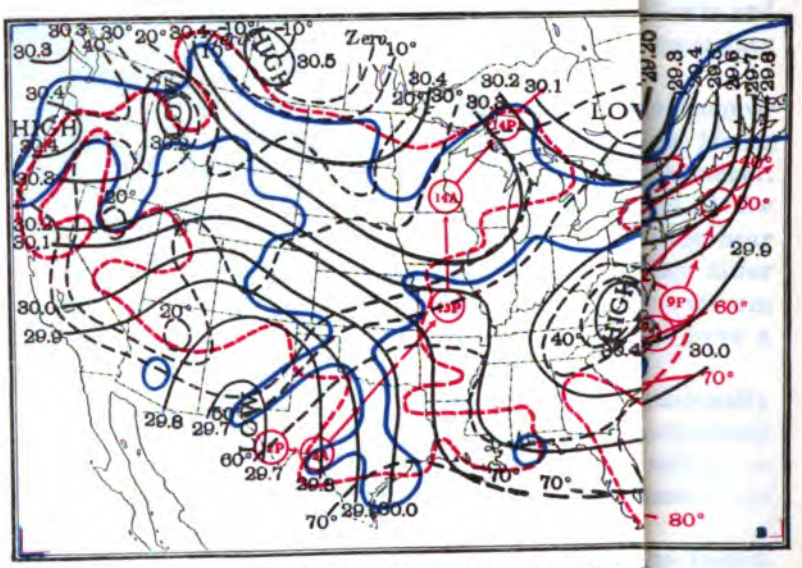

FIG. 43.—November 12, 1909, southwest LOW. Case I.

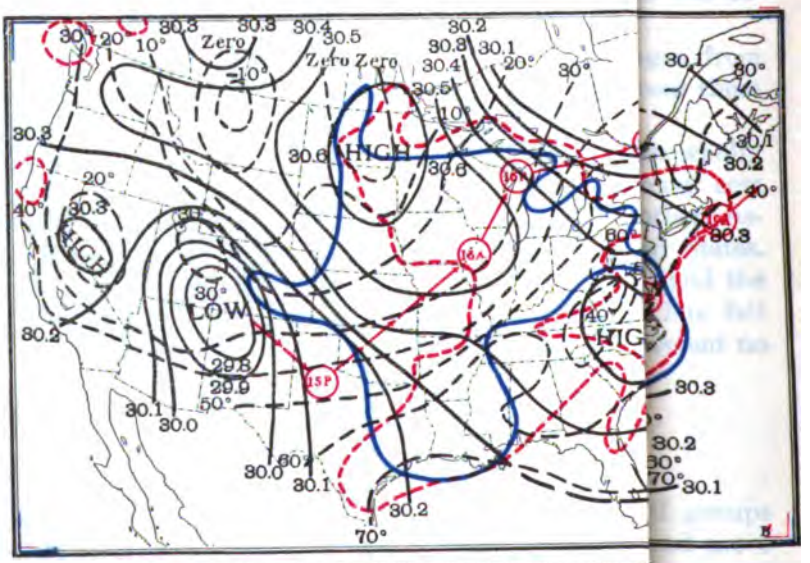

FIG. 44.—November 15, 1909, southwest LOW. Case N.

Southwest LOWS in

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ber of the LOWS belonging to the Pacific and Rocky Mountain groups pass southeastward to Kansas, Oklahoma, and the Texas Panhandle country and even Arkansas, before recurving to the northeast. When these LOWS are not attended by a HIGH in their immediate rear, and the pressure gradients are generally weak in all directions, they present one of the most difficult types with which the forecaster has to do; difficult in the sense that when a LOW is about to recurve the indications as to the direction of its movements are very indefinite, and also because of the fact that once the LOW begins to move on its new path the attendant rain area spreads to the northeast with very great rapidity. This is also true of practically all LOWS that originate in the Gulf States, provided the pressure distribution over the northeastern part of the country is favorable. It becomes necessary, therefore, if the forecaster aims to have his forecasts reach the public before the rain, to anticipate very closely the action of the southwest LOW within the coming 24 hours. Not all LOWS that reach the region in question cause precipitation; hence, the presence of a LOW is not of itself an indication of the beginning of precipitation. If precipitation has already begun, and there is a 12-hour pressure fall of 0.10 inch or more in the region about the center of the LOW, the forecast is much simplified, but in the absence of these guides the forecaster must rely upon his knowledge of the conditions under which LOWS develop in the southwest, and such knowledge can be obtained only by close personal study of the weather maps. There are a number of combinations of the HIGH and the LOW involved; we can do no more than point out some of the most important and let the reader draw his own conclusions. Practically all of the illustrations used are confined to the month of November, but the principles which obtain in that month hold for the remainder of the cold months.

(1) Figure 43, Weather map, November 12, 1909: A single LOW with weak gradients central at El Paso. Two HIGHS; one directly north, crest over Montana; the second over the Middle Atlantic States; saddle formation between the two HIGHS. This pressure distribution gives rain northeastward from west Texas to the upper Lakes, particularly on the southeast front of the Montana HIGH.[1]

(2) Figure 44, Weather map, November 15, 1909: Single LOW central over northwestern New Mexico and southwestern Colorado. HIGHS, two; one northeast over Dakotas, and the other over the Carolinas and Virginia. Much the same as No. 1. General rains.

(3) Figure 45, Weather map of November 19, 1907: One LOW with two centers: (1) Mouth of Rio Grande and (2) northern New Mex-

[1] In the six figures, Nos. 43–49, the areas of 24 and 36 hour rainfall following the dates of the maps are shown; the areas of the 24-hour rainfall being in blue and of the 36-hour rainfall, corresponding to the second forecast period, in red.

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ico. A single HIGH over the upper Lake region, moving eastward. Apparently that movement operates to open a path for the LOW to the northeast, as shown. Abundant precipitation follows.

(4) Figure 46, Weather map of November 15, 1910: Two LOWS, one mouth of Rio Grande, the other over southern Utah. A well-defined HIGH, axis north-south, Manitoba to northwest Missouri. The HIGH moved very slowly, as may be seen from the figure. On the 18th a second HIGH moved in from the Canadian Northwest. (See the path of HIGH No. 2.) The apparent influence of the two HIGHS is to retard and prevent from developing both the Rio Grande and the Utah LOWS. Note that the interval between the disappearance of HIGH No. 1 and the appearance of HIGH No. 2 was one of accelerated movement of both LOWS.

(5) Figure 47, Weather map, November 7, 1911: Single LOW, mouth of Rio Grande. Single HIGH along eastern slope Nebraska to the Texas Panhandle. The HIGH is a well-defined one and is moving northeastward; apparently it operates to keep the LOW well to the south and the latter is forced to take the outside course, viz, east-northeast to the Carolinas.

(6) Figure 48, Weather map, November 17, 1907: Low on Texas coast. Single HIGH to the northeast central over West Virginia, with approximately circular isobars. This we consider the ideal combination for a rapid advance of the rain area to the northeast. Rain first period as far as southern Pennsylvania and to New England second period.[1]

In the above group of combinations we began with LOWS central west of the 105th meridian and the HIGHS to the northeast and east. When HIGHS are thus disposed there is certain to be a break in the continuity of the pressure distribution between them, and this formation seems to favor the easy passage of a LOW and consequently the early development of rain areas. With a single unbroken HIGH to the northeast, as in No. 3, and especially when the HIGH is marked to continue its eastward movement, the forecast is plain. Combinations 4 and 5 illustrate the modifying effect of a well-defined HIGH that is marked to occupy some portion of the normal path of the LOW, and thus block the latter and shunt it off to the southeast. And finally in No. 6 we give the ideal combination for general rains advancing rapidly over Tennessee and the Ohio Valley in cold weather.

Let us next consider the type of southwest LOW characterized by one LOW over the Texas panhandle and a second center of the same original LOW central over Minnesota. The division of the LOW into two centers is the result of the southeastward advance of an anallobar. See weather map of November 27, 1907. The HIGH in such cases generally covers the Middle and South Atlantic States; its longer axis may be north-south or east-west. It has been the experience of the

[1] The terms "first" and "second" periods are explained on p. 279.

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writer that with a north-south axis, particularly if the latter has not passed to the eastward of the Appalachians, the area of precipitation advances slower than is the case with the longer axis of the HIGH extending in an east-west direction. The wind circulation of the latter would seem to be more favorable to precipitation than in the case first named. Examples: November 9, 1907 a; November 22, 1908 a; November 22, 1911 a; and November 5, 1912 a.

Generally the two LOWS pursue independent courses and precipitation must be forecast accordingly. Sometimes a ridge of relatively high pressure separates them. In this separating ridge no precipitation occurs, but it is quite impossible to foresee the exact limits of the ridge.

East Gulf lows.—The east Gulf LOWS form a group that apparently originates farther to the eastward and in slightly lower latitudes than the Texas LOWS, although it seems quite probable that they form in connection with troughs of low pressure that move from west to east across the country. We have before mentioned the fact that occasionally the northern LOW, in an irregularly shaped trough, will die away, and simultaneously there will be developed a very intense LOW over the Gulf of Mexico or along the Gulf coast. These secondary developments are not always apparent on the a. m. maps; hence the necessity of obtaining special reports in the afternoon from the South. The best clew to a southern development is the decrease in intensity of the northern LOW, as shown by wind velocities, when they become less than are indicated by the barometric gradients, and a reduction in the speed of the eastward movement. The severe Lake storm of November, 1913, was an example of this sort, and a somewhat similar storm occurred on February 28, 1914. In connection with the storm of February 28–March 1, 1914, charts showing the hourly pressure fall at Weather Bureau stations east of the Mississippi were prepared from the barograph records. These show a very pronounced increase in the rate of fall of the barometer over the South, and a corresponding decrease over the North. (See figs. 134–146 and the discussion thereon in Ch. VIII.) The initial pressures over the North were relatively low, however, so that even with a diminished rate of fall as the southern katallobar advanced northward, pressures in the North of an extraordinary low level resulted, and accordingly a storm of great violence ensued.

South Atlantic lows.—The south Atlantic LOWS form but a small percentage of the total number; yet, owing to the fact that they threaten the whole eastern seaboard, it becomes most important that the first symptoms of their development be detected. These are not early apparent; rarely are they visible on the a. m. maps, but, like the southern development in the southern and of a barometric trough

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mentioned in the preceding paragraph, they are most likely to occur during the afternoon, and will thus first appear on the night map.

Under the topic "High Winds," Chapter VIII, Mr. Edward H. Bowie describes a pressure distribution that foreshadows the development of a south Atlantic LOW, and illustrates it by maps. (See figs. 129 and 130, Ch. VIII.)

Other LOWS of the south Atlantic group develop in the trough of low pressure which extends southward from the primary LOW that is passing over the northern circuit. Still others move eastward across the Gulf States and emerge along the coast in the vicinity of Cape Hatteras. The forecasts of rain and temperature changes from these LOWS are attended by much uncertainty. The forecasts of high winds will be discussed in Chapter VIII.

HIGHS.

Highs, cause of.—Ferrell held the opinion that HIGHS do not generally depend directly upon cyclones, but only indirectly, and directly upon low temperature.[1] Prof. Milham in his recent work, "Meteorology," summarizes the causes of HIGHS as follows: (1) They may be caused by LOWS; (2) they may be caused by the congestion of poleward-moving currents; (3) they may be caused by radiation; and (4) they may be caused by *counter* currents, as suggested by Bigelow.

Prof. Milham points out that if the HIGH is due to the accumulation of air from LOWS or to radiation (causes one and three) it is gravity which supplies the energy. If HIGHS are due to the congestion of poleward-moving air currents, then the energy comes from the general system. Finally, if they are due to the counter currents (cause four), then the source of energy is the relative displacement of masses of warm air and cold air, respectively. (Milham, Meteorology, pp. 312–315.) The observant forecaster can add but little of importance toward clearing up the source of energy of the HIGH. Inasmuch, however, as HIGHS seemingly originate mostly in those places where terrestrial radiation is active, viz, in the clear, dry air of the northern Rocky Mountain region, it seems reasonable to assume that radiation to space has an important bearing upon the formation and maintenance of HIGHS. The close relationship of the HIGH and the LOW has already been referred to in this work; it is evident that a satisfactory explanation of either member of the couple must account for the formation and maintenance of the other. Such explanation is not yet at hand.

[1] A Popular Treatise on the Winds, New York, 1889, p. 344.

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Highs, movement of.—Lack of movement at the center of a HIGH is sometimes the result of a continuous rise in pressure extending over 48 to 72 hours. Such a condition is occasionally observed north of Montana, as illustrated in the two cases given below. The first case is that of February 12, 1904:

Pressure and temperature changes at Edmonton, Alberta, Feb. 12–14, 1904.

Date.	Pressure (sea level).	12-hour change.	Temperature.
			° F.
Feb. 12, a. m.	9.82	−0.38	−10
p. m.	0.22	+0.42	−10
Feb. 13, a. m.	0.38	+0.14	−12
p. m.	0.56	+0.20	−14
Feb. 14, a. m.	1.04	+0.48	−40
p. m.	0.54	−0.52	−14

Total rise in pressure in the 48 hours, 1.24 inches. Fall in temperature, 30° F.

The change in the next 12 hours was a fall of 0.48 inch. There was no indication on the synoptic charts of a fall intervening between the afternoon of the 12th and the morning of the 14th. The center of the HIGH was continuously at Edmonton, though the isobars projected southeastward, in elliptical loops, reaching Oklahoma by the afternoon of the 14th and forming a HIGH of great geographic extent, reaching, as it did, from the extreme northern boundary of the United States to the Gulf of Mexico.

Another example showing a continuous rise for 72 hours is given below:

Pressure and temperature changes at Edmonton, Province of Alberta.

Dates.	Pressure (inches).	2-hour change.	Temperature.
			° F.
Jan. 12, 1896, a. m.	30.10	−0.08	20
p. m.	30.14	[1] 0.06	22
Jan. 13, 1896, a. m.	30.62	0.46	− 6
p. m.	30.84	0.24	−12
Jan. 14, 1896, a. m.	31.02	0.16	−22
p. m.	31.12	0.12	−28
Jan. 15, 1896, a. m.	31.22	0.08	−44
p. m.	30.90	−0.34	−34

[1] Values without sign are plus.

Total rise in pressure in 72 hours, 1.12 inches. Fall in temperature, 66° F

Unlike the first example this HIGH did not at any time get far away from Alberta and neighboring Provinces. Pressure was continuously low along the Pacific coast and finally, on the 18th, a LOW, with minimum pressure below 29.50 inches, occupied the region of the great HIGH of three days previous.

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In order to ascertain whether the surface observations afford any clue to the rapid movement of HIGHS we have selected from the charts of the Monthly Weather Review for the 10 years 1904–1913 all cases where the plotted movement of the HIGH equaled or exceeded 750 miles in 12 hours. In all, 85 cases were found and examined in detail. The detailed examination makes it quite clear that very many of the charted tracks do not represent a progression of the HIGH from one point to another. The rapid movement is, in a number of cases, apparent rather than real, as we shall explain.

In a large area of high pressure—large in the sense that the inner isobar incloses an area of 50,000 to 100,000 square miles—there are often found isolated places where, due to some local condition or possibly to a faulty reduction to sea level, the sea-level pressure is a few hundredths of an inch higher than the general pressure within the inner isobar. It is customary to designate such local regions of maximum pressure as the center of the HIGH, even if the excess pressure appears at but a single station. In a case in point, February 17, 1905, a. m. map, the single station was Yellowstone and the sea-level pressure at this station was 30.60 inches, whereas at most of the surrounding stations it was but 30.58 inches. In the succeeding 12 hours the pressure in the northern end of the HIGH fell slightly, but did not change at the southern end. As a consequence, the center of the HIGH 12 hours later was placed at Dodge City, Kans., with sea-level pressure at 30.58 inches; which happens to be exactly the value it had 12 hours earlier, when the center of the HIGH was placed at Yellowstone with a sea-level pressure of 30.60 inches, as above stated. Thus it comes about that the records show a movement of the center of the HIGH from Yellowstone to Dodge City in 12 hours, or at the rate of 62 miles an hour. It seems perfectly obvious that there was no progressive motion of the HIGH.

Another case of an apparent movement of the center of a HIGH at the velocity of 80 miles an hour is afforded by the maps of March 2–3, 1907. On the first-named map, p. m. 2d, a HIGH, 30.30 inches, was central at Spokane, Wash. The isobars, however, looped far to the eastward, and the pressure gradient was very slight. The map of the succeeding 12-hour period shows the center of the HIGH to be at Huron, S. Dak. To effect this transformation required but a slight fall to the westward of the central portion of the HIGH, on the p. m. map of March 2, 1907, and a small rise to the eastward.

Perhaps the most usual and effective method of shifting the HIGH from place to place is through rising pressure in the front and falling pressure in the rear. The usual order of sequence in a west-east direction is HIGH-LOW-HIGH, as graphically illustrated in Weather Bureau Bulletin No. 20, page 29. In the disposition there shown the eastward HIGH contributes a supply of air to the LOW, which, accord-

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ing to theory, ascends and flows off laterally at the top of the cyclonic system. It is inferred that the direction of the lateral outflow at the top is controlled by the general winds at the altitude at which such outflow occurs. Definite information, however, is lacking, but of the following facts there is abundant confirmatory evidence, viz, (1) when a LOW advances eastward it draws air tangentially from the eastern HIGH which may be in immediate contact with it (the warm southeast winds on the front), and (2) that air flows tangentially into or toward the LOW from the western HIGH (the cold northwest winds in the rear). Obviously this process must eventually result in the dissolution of both HIGHS.

In any event the movement of the anticyclonic air mass appears to be controlled almost wholly by the cyclonic activity which is going on on its front and rear, respectively.

One of the conditions which appear to accelerate the movement of LOWS is also efficient in producing an apparent rapid movement of HIGHS. This condition is the looping of the isobars in a definite direction far in advance of the center of the HIGH. In the case of HIGHS we may conceive of the process as a building up at some central region and a running down or spreading out by the force of gravity from that central point. The running down of HIGHS is manifested on the weather maps by the looping of the isobars as above described. We may use an illustration drawn from the methods of topography to make our meaning clear. Let us conceive that the air which descends in the center of a HIGH spreads out in the direction of least resistance in the shape of successive terraces, so to speak, and that each terrace is bounded by an isobar. Not infrequently these so-called terraces spread a distance of 1,000 miles in advance of the center of the HIGH. If, now, pressure falls slightly at the center of the HIGH and rises slightly on the most distant terrace, the center of the HIGH is immediately transferred to the distant region, although there has been no transference of the mass of the atmosphere from one point to the other. (See also remarks on the disintegration of HIGHS.)

In practical forecasting it is important to know the rate of movement of HIGHS as well as of LOWS. The dual partnership that seems to exist between the HIGH and the LOW makes it almost impossible to consider separately the application of the principles involved in fast-moving HIGHS to forecasting. In general, we may say *that a fast-moving* HIGH *is not always attended by that marked drop in surface temperature that accompanies a* HIGH *moving with moderate speed.* A fast-moving HIGH, from the nature of the case, is presumptive evidence of the coming of a fast-moving LOW; therefore, there can be no decided change to lower temperature. The type of fast-moving HIGH

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above mentioned is one with circular or oval isobars and wholly within the United States. (See fig. 49, Weather Map of Dec. 19, 1914. See, also, map of Jan. 6, 1912 (a); Mar. 9, 1913 (a); Oct. 8, 1907 (a); and Dec. 9, 1908 (p).)

There is still another type of fast-moving HIGH, viz, the wedge-shaped HIGH of the British Northwest, that moves from that locality to the lower Missouri Valley in 24 hours and to the Gulf of Mexico in 48 hours. A characteristic HIGH of that type is shown in figure 50, Weather May of November 18, 1914. These HIGHS cause a sudden and decided fall in temperature throughout their respective paths and the reaction to higher temperature is almost immediate. (See chapter on "Cold Waves.")

Mention should also be made of what may be called false, or pseudo, HIGHS, viz, those HIGHS generally of small intensity which sometimes form immediately in the rear of fast-moving LOWS while the real HIGH is yet some distance away. (See map of Jan. 22, 1908.) In all such cases a second lowering of temperature will occur when the more distant HIGH reaches the meridian of the point. The so-called false HIGH generally merges with the real HIGH as the latter moves eastward.

Highs with increasing pressure at the center.—Pressure within the closed isobar in the central region of a HIGH is subject to many fluctuations, some of which are the result of causes that are obvious, while in other cases the cause of the marked increase at the center is not clearly comprehended. For convenience of discussion we will divide HIGHS that show a marked increase in pressure within the closed isobar encircling the central region into three classes, viz, (A) those highs in which pressure increases from a relatively low value at the point of origin to a relatively high value within 24 hours. We would call the A HIGHS the normal HIGHS; B HIGHS may be described as those which are occasionally built up at the center. These HIGHS are not associated with a marked lowering of surface temperature in their central portions, as in the case of A HIGHS. Pressure at the center may increase as much as two to three tenths of an inch from a relatively high value. Thus, on March 4, 1904, a HIGH central over Indiana, with maximum pressure of 30.58 inches, moved northeastward to Maine, maximum pressure increasing to 30.96 inches, which high value was maintained for 12 hours. Other cases are February 19–20, 1904, and November 27–28, 1914. While the B HIGHS are not important as a temperature control, they evidently exert considerable control on lows that may be approaching from the west or south. The uncertainty as to their weather control arises from the fact that unless they stagnate their influence is *nil*.

Reenforced or C highs.—These are a very important class to the forecaster, since they indicate marked changes in temperature when

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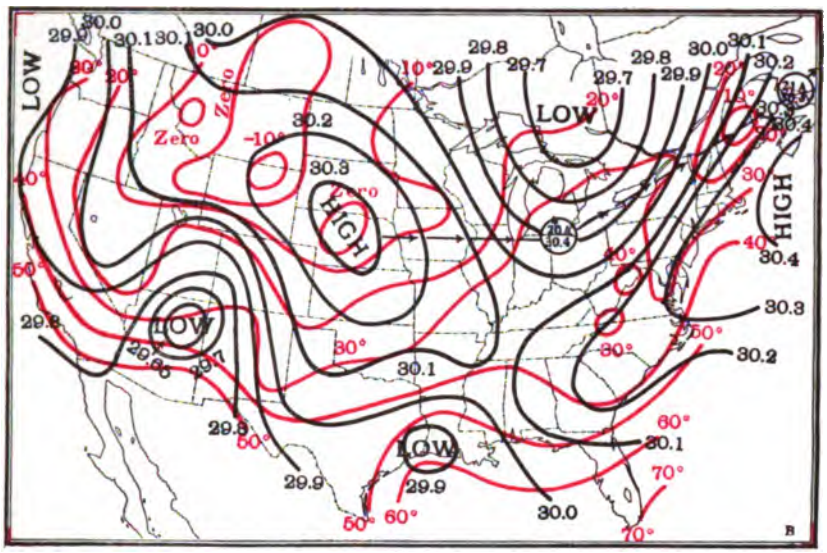

FIG. 49.—Rapid movement of HIGH, December 19, 1914.

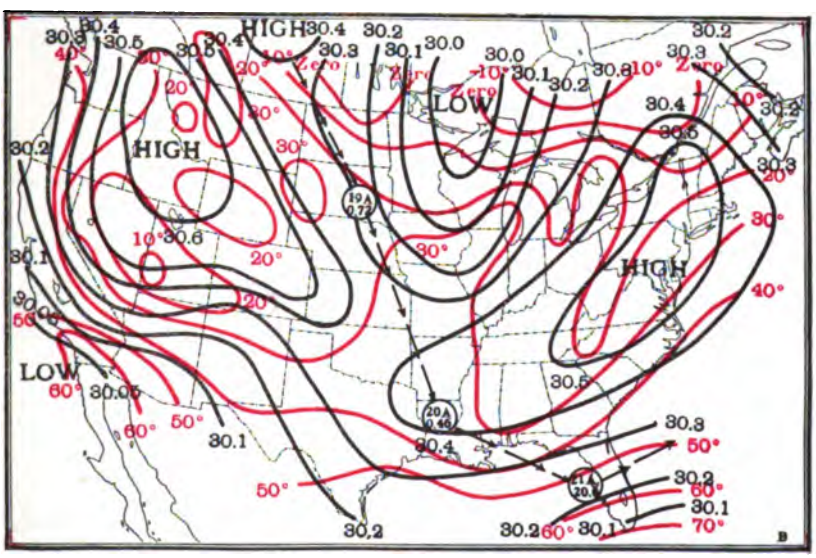

FIG. 50.—Rapidly moving HIGH of November 18, 1914.

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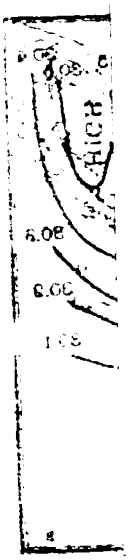

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the latter is already at a low value. Thus, with the prevailing temperatures at zero or below, forecasters are not overwatchful in issuing further cold-wave warnings, although this is sometimes done.

The following example illustrates the apparent influence of a slightly reinforced HIGH in connection with a further drop in the temperature closely following an original and marked depression of the temperature. The HIGH in question is No. X of Chart II, Monthly Weather Review, February, 1906. The circuitous path of that area on closer analysis is probably fictitious. The method of charting the tracks of HIGHS and LOWS that had until recently been followed is not adapted to portraying the fact that the center of a HIGH or LOW may be stationary at one and the same point for several consecutive 12-hour periods. We have redrawn the track in question and avoided the difficulty of showing a stationary condition by placing the dates and maximum pressures, respectively, within circles, which latter have been placed in the immediate vicinity of Winnipeg, and present the track of this HIGH as well as of a Great Basin HIGH in figure 29. We also give below a table of weather conditions at Winnipeg during the continuance of the HIGH. The latter first appeared in the vicinity of Battleford, Saskatchewan, on the morning of February 24, 1906, with sea-level pressure 30.32 inches; it advanced southeastward and appears on the p. m. map of the same date as central at Winnipeg, pressure 30.34 inches, a rise of 0.48 inch in the preceding 24 hours. The fall in temperature in the same time was 30° F. to a minimum of zero.

The weather at Winnipeg, Feb. 23–27, 1906.

Date.		Pressure.		Temperature.	Wind.		State of weather.
Day.	Map.	Sea level.	Change in last 12 hours.		Direction.	Velocity.	
23	a. m.	9.86	+0.20	4	W.	Light	Clear.
	p. m.	9.86	+0.02	30	SW.	do	Cloudy.
24	a. m.	0.28	+0.40	−6	W.	18 miles	Clear.
	p. m.	0.34	+0.06	Zero.	W.	Light	Do.
25	a. m.	0.34	−0.02	−14	SE.	do	Do.
	p. m.	0.44	+0.12	4	N.	8 miles	Do.
26	a. m.	0.66	+0.22	−18	N.	Light	Do.
	p. m.	0.66	+0.02	−2	N.	do	Do.
27	a. m.	0.62	−0.06	−15	SE.	8 miles	Do.
	p. m.	0.12	−0.48	16	SE.	24 miles	Cloudy.

A very slight katallobar then passed over Manitoba between the evening of the 24th and the morning of the 25th, the pressure fall in which amounted to only 0.02 inch at Winnipeg, as shown in the table. Farther south the amplitude of the fall was greater. This small pressure fall apparently provided the opportunity for a second anallobar to follow the original, which we have noted as reaching Winnipeg on the afternoon of the 24th. The sequence is, therefore, (1) the original rise in pressure on the 24th that was associated

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with a fall in temperature from 30° to —6°; (2) a slight fall in pressure on the 25th; and (3) a second rise in pressure immediately following, causing a further reduction in temperature of 4°, from —14° to —18°. The crux of the matter is the slight fall in pressure, so small in this case that it might easily escape the notice of the forecaster, that prepares the way for a second rise in pressure and a further lowering of the temperature. The matter is further elucidated by the series of three charts, February 8, 9, and 10, 1906, respectively, reproduced as figures 51, 52, and 53. The significant feature of the map of the 8th is the juxtaposition of the two HIGHS in Manitoba. Temperatures, as may be seen, are well below zero. The separation of the HIGH into two centers is indicative of a slight break in the continuity of the pressure distribution in the HIGH. The p. m. map of the 8th (not reproduced) shows that there was a slight fall in pressure during the 8th in the valley of the Red River of the North, but not sufficient to disturb or alter the configuration of the isobars. By the 9th, as it will be seen, the pressure gradient between the two high centers of the 8th is considerably increased, amounting to about two-tenths of an inch, and the temperature has risen slightly. The conditions are now ripe for a further reduction of temperature. The fall at Devils Lake in the next 24 hours was from 2° above zero to 30° below, as may be seen from the map of the 10th.

Great Basin highs of winter.—Certain orographic features, as exemplified by the Great Basin, which term embraces small portions of southeastern Washington, southeastern Idaho, southeastern Oregon, practically all of Nevada, and western Utah, a strip along the eastern border of California and a large area in the southern part of the State, exert a marked influence upon HIGHS which come within its limits; the action of Great Basin HIGHS is probably partly due to geographic location and partly to the topographic features of the region. A cursory examination of the weather maps during the cold season will create the impression that Great Basin HIGHS are of a semipermanent character, persisting, as they often do, for 10 days or 2 weeks. It is believed their formation is indicated by an anallobar passing southeastward from British Columbia.

The magnitude of the Great Basin HIGH and the level of the barometer reached therein depend primarily upon the initial pressures at the time the crest of the anallobar is superposed upon the existing pressures. The initial impulse may come from Alberta, whence anallobars pass to the southward and spread out fan-shape to the east, south, and southwest; in any event, as soon as a HIGH of, say, 30.50 inches sea-level pressure is established in the Great Basin there is then apparently a general stagnation in the local surface currents. The air is very dry and, possibly through the effect

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of nocturnal radiation, the lower air layers are further cooled, while pressure rises by small increments each day for several days, although the process is not continuous. If, however, the ground is snow-covered, the conditions are more favorable than otherwise. In a few days, generally in less than a week, katallobars that move eastward across British Columbia touch the northern portion of the Great Basin and pressure begins to fall, slowly at first, and then more rapidly as the air is drawn across the mountains of Idaho and Montana to feed Alberta LOWS. The effect of this slow fall in the northern portion of the basin, while pressure in the central and southern portion is stationary or slowly rising, is to shift the center of the HIGH little by little to the southeastward, until finally it reaches the vicinity of Salt Lake City, or passes southeastward over the elevated table-lands of Wyoming.

As soon as the trough of the first katallobar has passed, a reaction to higher pressure sets in over the northern portion of the Great Basin, and thus the HIGH is periodically renewed. The characteristic feature of the Great Basin HIGH is its ability to maintain itself for several days practically unchanged, and this ability is due, as we have suggested, to physiographic features which are responsible for the low surface temperatures and the lack of air drainage from the districts west of the Sierras, whence a supply of warm air is had. The path of a typical Great Basin HIGH is plotted in figure 29, and we give below, as illuminating the weather conditions at a representative station in the Great Basin, viz, Boise, Idaho, weather statistics for the period January 11–20, 1903, during which time the original HIGH was twice renewed at its northern extremity, and a third renewal was in progress at the close of the period.

Weather statistics, Boise, Idaho, Jan. 11–20, 1903.

Date.		Pressure.		Temperature.	Wind.		State of the weather.
Day.	Map.	Sea level.	Change in last 12 hours.		Direction.	Velocity.	
11	a. m.	30.32	+0.10	24	W.	Light	Foggy.
	p. m.	30.46	+0.16	30	SW.	6 miles	Cloudy.
12	a. m.	30.62	+0.14	26	S.	Light	Do.
	p. m.	30.68	+0.08	28	W.	do	Do.
13	a. m.	30.70	+0.00	26	SE.	8 miles	Do.
	p. m.	30.68	+0.00	30	E.	Light	Do.
14	a. m.	30.64	−0.06	22	SE.	do	Clear.
	p. m.	30.48	−0 14	32	S.	do	Partly cloudy.
15	a. m.	30.36	−0.14	20	NW.	do	Foggy.
	p. m.	30.30	−0.04	22	W.	do	Do.
16	a. m.	30.34	+0.02	22	NW.	do	Cloudy.
	p. m.	30.40	+0.08	24	NW.	do	Do.
17	a. m.	30.46	+0.04	22	S.	do	Do.
	p. m.	30.48	+0.04	22	W.	do	Do.
18	a. m.	30.58	+0.08	22	SW.	do	Do.
	p. m.	30.34	−0.22	30	N.	do	Do.
19	a. m.	30.28	−0.06	24	NW.	do	Do.
	p. m.	30.32	+0.06	24	W.	do	Do.
20	a. m.	30.30	−0.04	26	NW.	do	Snow.
	p. m.	30.22	−0.06	32	N.	do	Rain.

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Forecasting value of Great Basin highs.—It has long been recognized by forecasters that, while a HIGH occupies the Great Basin, Alberta and north Pacific LOWS will move eastward over the northern circuit and that fair and moderately warm weather will prevail over the Plains States; moreover a HIGH firmly lodged in the Great Basin appears to prevent north Pacific LOWS, which are so essential to the causation of rain on the Pacific coast, from moving southeastward over Oregon and California.

Additional remarks on Great Basin HIGHS by District Forecaster F. H. Brandenburg will be found in Chapter XII.

Another group of very important HIGHS are those which move into the Lake region, especially in the spring. These HIGHS are discussed rather fully by Prof. Cox, from whose manuscript the following is taken:

LAKE REGION HIGHS OF SPRING.

Sometimes HIGHS in spring which first appear in the British Northwest or come in from the north Pacific coast will develop in intensity as they move southeastward across the Lake region and control the weather conditions in the eastern half of the country for nearly a week. The pressure increases over the Lakes because the isobaric surfaces there become depressed, due in that season to the relatively cool air, and this depression aloft is filled in with air transported by the westerlies of the higher altitudes, thus producing increased pressure at the surface of the earth. These HIGHS after reaching the Lake region sometimes will drift slowly southeastward across the Middle Atlantic States into the permanent HIGH over the south Atlantic. Frequently rain will follow over the Middle West on the southwest side of the HIGH, but if the HIGH takes a more southerly course after reaching the Lakes, the rain area is not likely to advance eastward. Such HIGHS will often completely break up a trough of low pressure advancing from the west. (Apr. 17–22, 1913; May 7–12, 1913; and June 7–10, 1913.) These HIGHS often remain stationary over the Lake region and keep the rain from advancing until there is evidence of a breaking away in the shape of falling pressure in the sections west of the Lakes. Until the barometer does begin to fall west of the Lakes, regardless of how much rain is falling in the west, fair weather may be expected to continue in the Lake region. Moreover, as a disturbance approaches from the west or southwest, accompanied by rain, the beginning of rain in the spring is much delayed in the Lake region; in fact, it is often delayed until the storm center approaches quite closely or until the wind shifts to southerly as the storm moves northeastward. (June 1–5, 1908; Apr. 23–26, 1905; May 3–6, 1910; May 5–6, 1900.) The reason for the persistent fair weather in the Lake region at this season is due to the influence of the HIGH, because the winds blowing out of it over a water surface are warmed considerably as they reach and pass over the land, and with the rising temperature the air has a much greater capacity for moisture. It is not a fact, then, that easterly winds, at least in the spring and early summer, indicate precipitation in the Great Lakes region, but instead they often presage a protracted period of fair weather.

In the spring, when a HIGH appears in the British Northwest and a LOW in the south or southwest, the HIGH as it moves eastward overspreads the entire Lake region, but as the season advances into late May and June, with increasing temperature of the water, it is less and less likely to be felt over the

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southern portion of the Lake region, especially when an area of high pressure overlies the southern or southeastern States. The 12-hour pressure-change map generally indicates the progress of the movement of these HIGHS, as in other types of maps. A strong rise in pressure in the northwest and a fall over the middle Mississippi Valley, even though slight, are certain indications of a HIGH extending in its eastward movement over the southern limits of the Lake region and even beyond.

HUDSON BAY HIGHS.

The class of HIGHS hereunder considered differs somewhat from the ordinary type in the following respects:

The crest of the HIGH appears far to the westward, about the ninety-fifth meridian, and the area of temperature fall is not coincident with the area of 12-hour pressure rise. The HIGH extends in an east-west direction, with its center generally north of the Great Lakes. It apparently originates in Manitoba or eastern Saskatchewan, and attains its greatest development in February in the region about Hudson Bay. Pressure may be as high as 30.60 inches sea level, at the beginning and it may increase to 30.80 or 30.90 inches. Temperatures at White River are very low, 40° or 50° below zero. This HIGH differs from another type, which has the same apparent point of origin, in the fact that the latter moves southward into the United States, whereas the first-named does not, except that the inner isobar may descend over the Valley of the Red River of the North, but the movement is generally east until the Upper Lakes are passed; thence the movement is southeast, particularly if there has been a fall in pressure in the Middle Atlantic States or along the coast.

Highs, in their temperature relations.—It is one of the rudimentary propositions in forecasting that a HIGH is associated with a lowering of the surface temperature in its path and frequently over extended regions on either side. While this fact is known to everyone who has had any experience with daily weather maps, yet the degree of lowering of the temperature and the details that are associated with the different seasons are not so well known, and that is our excuse for these paragraphs.

The use of the expression, "cold HIGH" in this work is not equivalent to the admission that there are "warm" HIGHS, although it does appear that there are different degrees of cold associated with HIGHS, and that in exceptional cases the surface temperature within a HIGH may be above the normal—see the South Atlantic States HIGH of April 27, 1915, and other HIGHS in that region during the summer months.

In order to show the seasonal differences in the reduction of temperature associated with HIGHS, we have prepared a series of eight charts showing the amount of surface cooling associated with the

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HIGHS of February 4–7, 1906—a winter type—and of July 15–18, 1896—a summer type—respectively. These charts (see figs. 54 to 61) show the inner and the next consecutive isobar of the HIGH in black, and the lowering of the temperature in red lines; the line of no change in temperature is shown by a heavy black line.

Considering, first, the winter series, it is to be remarked that the reduction in temperature is widespread and affects the entire region east of the Rocky Mountains; moreover, that while the crest of the HIGH moved almost due east across the Lake region, there was a sharp fall in temperature over the southern Plains States and Texas, reaching the Gulf coast on February 6, and that there is considerable overlapping of the areas of temperature fall from day to day. Thus, on February 6, there is an area of 20 degrees fall over Minnesota and North Dakota, in which territory temperature has fallen for three consecutive days. On this same date it is noted that temperature has begun to rise on the Pacific coast, which rise had advanced to the Dakotas by the 7th.

The summer series, July 15–18, 1896, figures 58–61, show that the fall in temperature associated with a HIGH in the summer is less than half what it is in winter, and that the areas affected are very much less. Also, that the amplitude of the fall is greatly reduced as the HIGH reaches Atlantic coast districts. One may also observe in both winter and summer the modifying effect of local topographic conditions.

THE DISINTEGRATION OF HIGHS.

The natural function of HIGHS seems to be to serve as feeders of LOWS, and it is almost wholly in the exercise of that function that they disintegrate. They will decay whenever for one reason or another they are shunted off the main track followed by LOWS. In the cold season dead or disintegrating HIGHS occupy the Plateau and Rocky Mountain regions and occasionally the Gulf and South Atlantic States. The decay, we believe, is due to the fact that when a HIGH ceases to follow closely a LOW it loses any inherent energy that it may have had and naturally becomes an inert mass of air.

The amount of lowering of temperature that is associated with different HIGHS seems to vary with the origin of the HIGH. The writer has before pointed out (Monthly Weather Review, vol. 36, p. 54) that HIGHS passing inland from the Pacific Ocean are not associated with severe cold as they move across the continent. Hence, as a matter of forecasting, the origin of the HIGH and the path of the LOW which precedes it must be considered. This subject will be further treated in the chapter on cold waves.

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INDICATIONS FROM HIGHS.

An increase in pressure at the origin of a HIGH, or the place of its first appearance on the weather maps, extending over two successive maps, is an indication of the building of a strong HIGH. Likewise, a rise in pressure that extends over two consecutive maps at any time during the eastward or southeastward movement of a HIGH indicates that the speed of the HIGH will diminish and it may present an unyielding front to a LOW that threatens to advance into it. A third precept of similar character is, when the central pressure in a HIGH increases during the day hours—that is, when the increase shows on the p. m. map—such increase may be taken as the equivalent of an increase in the intensity of the HIGH. Normally, the afternoon pressures are a little lower than the morning pressures. Whenever, then, the normal diurnal tendency to lower pressures on the p. m. map is overcome, and even reversed, it is clear evidence of an increase in the intensity of the HIGH.

Trend of the isobars in a high.—Isobars trending north-south facilitate the transfer of cold air to southern regions on the eastern side of the HIGH and, conversely, of warm air to higher latitudes on the west side of the HIGH.

Reenforced highs.—The point to be carefully observed as indicating a fresh fall in temperature is a slight fall in pressure. HIGHS in the British Northwest, with two centers in immediate juxtaposition, indicate the probability of a fall in pressure between the two independent centers. (See figs. 51, 52, and 53.)

Great Basin highs.—See District Forecaster Brandenburg's note in Chapter XII.

Rain in southwest quadrant of a high.—A circular HIGH moving toward the east rather rapidly in, say, latitude 35° sometimes gives light rain, beginning in Kansas or Arkansas and continuing thence eastward, sometimes even to the Atlantic coast. Somewhat the same situation, only in a more intensified form, causes heavy and continuous rains in Texas and the Southwest, as in the closing days of June, 1899. (See the weather maps of June 27, 28, 29, and 30 of that year.) In the case first named a LOW to the southwest of the HIGH is not visible; in the second case there is an ill-defined LOW along the Texas coast or to the westward over southeastern New Mexico. This combination—well-defined HIGH to the northeast and ill-defined LOW in either of the places named—seems to cause heavy downpours of rain over Texas and the Southwest, especially in northeast New Mexico. (See the maps of May 1, 1914.) It is a rather curious fact that, notwithstanding the arid character of southwestern Texas, some of the heaviest rains in the United States fall over that territory.

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THE TEMPERATURE AND THE WIND ELEMENTS IN FORECASTING.

While few definite rules can be laid down as regards the influences of surface temperature on the course of a LOW, it may be confidently asserted that a LOW will rarely or never move into a region of *falling* temperature. In general, the movement of the LOW is more apt to be parallel to the isotherms than across them. A well-developed LOW in the Mississippi Valley, however, is able to alter the course of the isotherms as it moves northeastward; hence, this rule should not be taken too literally.

The late Prof. E. B. Garriott, in 1895, formulated a rule regarding the influence of temperature on the course of a LOW as follows:

> Low areas will not cross isotherms which represent lower temperature than that which obtains about the low center.

Prof. Garriott, in 1894, credits Lieut. (now Col.) Glassford, of the United States Signal Corps, with a somewhat similar rule, as follows:

> A storm center will not cross an isotherm which descends southward in its front.

Garriott's rule, as well as Glassford's, would seem to be applicable to the Rocky Mountain and Plateau regions and in a lesser degree to the Plains States, but not east of the Mississippi Valley.

Prof. COX says, "Rain seems to follow a HIGH that has produced general frosts." (See p. 307.) This statement bears out the observation frequently made that after several frosty mornings, particularly if the ground be bare of snow, rain is quite likely to follow the advent of almost any kind of a LOW that may be approaching from the west or southwest.

It is the view of the writer that while the value of the temperature element in forecasting the weather in the United States is not great, its true significance has not yet been thoroughly investigated. The difficulty arises from the fact that it is not easy to eliminate the effect of diurnal variation and peculiarities due to surface cover and other purely local causes. The morning temperatures east of the Mississippi Valley are fairly satisfactory. These readings, it may be remembered, are made at 8 a. m., seventy-fifth meridian time, an hour that is not far distant from the hour at which the daily minimum occurs. The 8 p. m., seventy-fifth meridian time, temperatures that appear on the 8 p. m. weather maps, on the other hand, are unsatisfactory, especially in the Rocky Mountain region and thence westward, since they correspond quite closely with the daily maxima in those regions.

There is one phase of the subject that is important in connection with forecasts of precipitation, viz, a rise in temperature to the east of a trough of low pressure in the same forecast period for which

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precipitation has also been forecast at times seems to be inimical to the occurrence of precipitation in that period. Generalized broadly, this idea may be expressed as follows: Precipitation is slow in beginning on the warm side of a trough of low pressure or a long oval LOW whose major axis extends in a northeast-southwest direction.

The explanation generally offered is that in barometric configurations of the kind described, the winds on the warm side of the depression are southerly and probably without convective ascent. The beginning of precipitation is therefore deferred until the trough line of the depression crosses the place, with the attendant shift of the winds to a westerly quarter.

A snow covering, through its influence on the surface temperature, has a tendency to build up HIGHS and apparently to cause them to linger over snow-covered surfaces longer than over bare surfaces. This problem has not, however, been studied in detail.

THE WIND ELEMENT IN FORECASTING.

Considering that the relation of wind force to barometric gradient is one of the fundamental questions in modern meteorology, it is rather surprising that so little use is made of it in the practice of Weather Bureau forecasters. We are inclined to believe that the reason therefor arises from the lack of accord between the wind directions and the isobars so often noted on the daily map. It has been customary, and we believe rightly, to ascribe the inconsistencies above mentioned to irregularities in the surface of the earth that produce variations in the coefficient of friction, and these variations from one point to another produce disturbances of the angle between the isobars and the wind. To the natural irregularities in the surface of the earth there has been added a series of artificial irregularities due to the placing of wind instruments on the roofs of tall office buildings in the larger cities. These exposures vary in altitude above the surface of the ground and also above the artificial surface created by the roofs of surrounding buildings, so that there can be no uniformity of exposure, and we must therefore expect rather frequent cases of departure in both direction and speed of the wind from the theoretical wind due to the pressure distribution. Of course, the wind direction in regions of indifferent pressure gradients gives early and valuable information of the formation of a cyclonic circulation. Occasionally a weak cyclonic circulation on the morning map is the first suggestion of thunderstorm formation later in the day.

It would be a step in advance to determine for each station the deviations from the normal winds that occur at that station, thus

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forming a system of local corrections that would be valuable to a forecaster in an attempt to use the wind element at its true value.

The force of the wind as recorded by anemometers placed on the roofs of tall buildings also lacks homogeneity and thus discourages, in the short time available for consideration during the forecast hour, any attempt at correlating wind velocities and pressure gradients. The forecaster is generally acquainted with the local exposures and with the fact that for the same barometric gradient the velocities are considerably higher at some points than at others, due to differences in local exposure, and he acts accordingly.

A consideration of the force of the wind in connection with the pressure distribution forms a most important part in the scheme of M. Gabriel Guilbert[1] for forecasting the weather. The details of M. Guilbert's scheme are fully set forth in the reference given below, and Sir Napier Shaw discusses its application to weather forecasting in Great Britain.[2]

In the United States Prof. F. J. Walz, of Louisville, Ky., has endeavored to apply M. Guilbert's system to the forecasting problem. Prof. Walz says:

I have practiced a little in trying to apply Guilbert's system to conditions in the central portion of the United States, but of course the values of the normal winds have not been computed for the various stations; also the anemometer exposures at the various stations are the causes of a considerable difference in winds reported, thus making it difficult to make comparisons with any adopted value of the normal wind. I used the values for normal winds adopted empirically by M. Guilbert and by converting them into the standard used in this country constructed a table as follows:

Gradient in hundredths of an inch per 172 statute miles.	Normal wind.
0.05	Under 6 miles an hour.
0.10	10
0.15	14
0.20	18
0.25	24
0.30	30
0.35	34
0.40	38
0.45	42
0.50	46
0.55	50
0.60	52

Other difficulties experienced in practically applying the method of normal winds are: Depressions frequently cover large areas in the United States, much larger, as a rule, than those passing over northern Europe, and hence our storms are not so concentrated and well marked in their dynamic action; and

[1] Principles of forecasting the weather, translated by O. L. Fassig, Monthly Weather Review, vol. 35, pp. 211–212.

[2] W. N. Shaw, forecasting weather. London: Constable, 1911.

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shallow depressions, with no marked strong winds, often give generous precipitation over large areas and become important formations, while the wind velocities, irregular or small, give no clue to their actual movement and behavior.

In addition to the difficulties pointed out by Prof. Walz, we would add that the scale of the weather maps in use by the Weather Bureau is not suited to easy computations of gradient per unit distance, and, moreover, that, inasmuch as the position of the isobars is frequently interpolated, there would be danger of the introduction of an error, in some cases of a magnitude great enough to obscure the small difference we might hope to detect. There would always be the possibility that, after all, the difference between the observed and the theoretical gradient force might be due to some local condition which would have no influence on the future intensity of the storm.

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CHAPTER VI.

COLD WAVES.

By HENRY J. COX, Professor of Meteorology.

[With contributions by District Forecasters John W. Smith, Isaac M. Cline, Frederick H. Brandenburg, Edward A. Beals, and George H. Willson.]

Cold wave defined 143
Extremes of minimum temperature in the United States 144
Verification of cold wave warnings in different sections 145
Cold waves—how they occur 149
Geographical distribution of 149
Frequency of 150
Influence of Great Lakes upon 151
Influence of thermometer exposure 152
Effect of variation of verification in different sections 153
Cold waves:
Influence of topography and proximity to ocean 153
Movement of, from Canadian Northwest 154
Various types of 156
Special conditions affecting the movement of cold waves 162
Charts used in forecasting 165
Forecasting cold waves in:
New England 169
West Gulf district 170
Denver district 171
North Pacific district 172
South Pacific district 173

COLD WAVES.

Cold wave defined.—The term "cold wave," as used by the Weather Bureau, means a 24-hour fall in temperature of 16°, 18°, or 20° within a 36-hour period and to varying limits of minimum temperature in different sections of the country, as shown by figures 62 and 63. The amount of fall and the degree of cold have been arbitrarily fixed with a view of properly protecting commercial and agricultural activities in the various districts.

There are great differences in the limiting temperature because of the wide variation in the winter cold throughout the country, as shown by figure 64, which indicates the lowest temperatures ever observed in the various sections, and as shown by figure 65, upon which appear the normal 8 a. m. temperature readings for the third decade of January, corresponding closely with the normal minima during this mid-winter period. It is especially interesting to note,

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in figure 65, how much lower these normal temperatures are at Moorhead, Minn., for instance, and in Manitoba, directly to the north, than in similar latitudes westward to the Rockies.

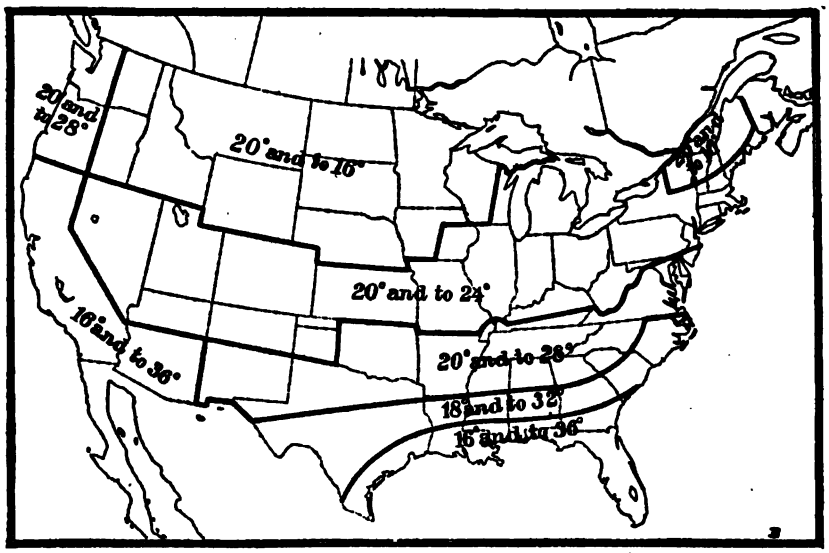

FIG. 62.—Cold-wave zones, March to November. Amount of fall and verifying limit.

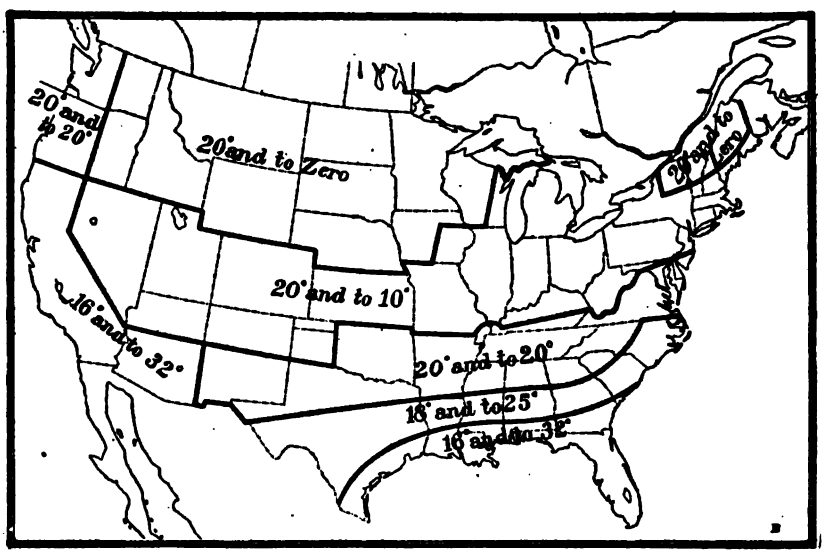

FIG. 63.—Cold-wave zones, December, January, and February. Amount of fall and verifying limit.

Extremes of minimum temperature in the United States.—The absolute minima in the Northwestern States east of the Rockies range from —40° to —60°, and in the northern portions of New England

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and New York State from —30° to —40°. Zero temperature has been noted in the extreme south in the Gulf region from Mobile to Tallahassee, and readings as low as 10° on a line passing from northeast to southwest through the north portion of the peninsula of Florida and through extreme southern Texas at the mouth of the Rio Grande, as shown by figure 64. The entire State of California, as well as the Florida peninsula, has, at some time, been visited by freezing temperature.

It is proper to compare the differences in the readings as they appear in figure 64 with the temperatures in figure 65, and in this comparison we find considerable harmony, the lowest minima and normals naturally being in the North and highest in the South, although the differences in figure 65 are, of course, not so great, because they represent normal or average readings rather than extremes, as shown in the first named. The change from north to south is not uniform in every case, especially near the Great Lakes and in the Far West, but this inequality is due to water influence and elevation. Roughly, the differences in absolute minimum temperature between the northern frontier and the north coast of the Gulf of Mexico exceed 50°, while the differences between the normals in similar sections range from 40° to 50°.

Verification of cold-wave warnings in different sections.[1]—The districts set off in figures 62 and 63 are arbitrarily selected as seemingly demanded by the public interests, and the readings to which the temperature is required to fall in 24 hours in order to verify cold waves in these districts conform rather roughly to the variations shown in figures 64 and 65. However, the differences from north to south between the limiting temperatures in figures 62 and 63 are not so great as between the minima in corresponding sections, as shown by figure 64, and between the normal morning temperatures, as shown by figure 65. This is mainly because the readings required to verify a cold wave in the North are not as much below the normal as in the South. Temperatures of 32° along the Gulf coast in Florida and in southern California at any time of the year are quite serious. While a fall to zero verifies a cold-wave warning in North Dakota and Minnesota, the normal winter minima at several points in this area are very close to zero, but in the extreme South these normal minima are 15° to 20° above the freezing point (32°—the verifying temperature). Crops in the Florida peninsula and in southern California are in growth during the entire winter and must be protected from low temperature, and this is the reason that warnings of falls to 32° are necessary. The limiting temperatures in the

[1] Under recent Instructions (No. 19, of 1916) the winter limiting minimum in certain sections has been made applicable to March cold waves.—Editor.

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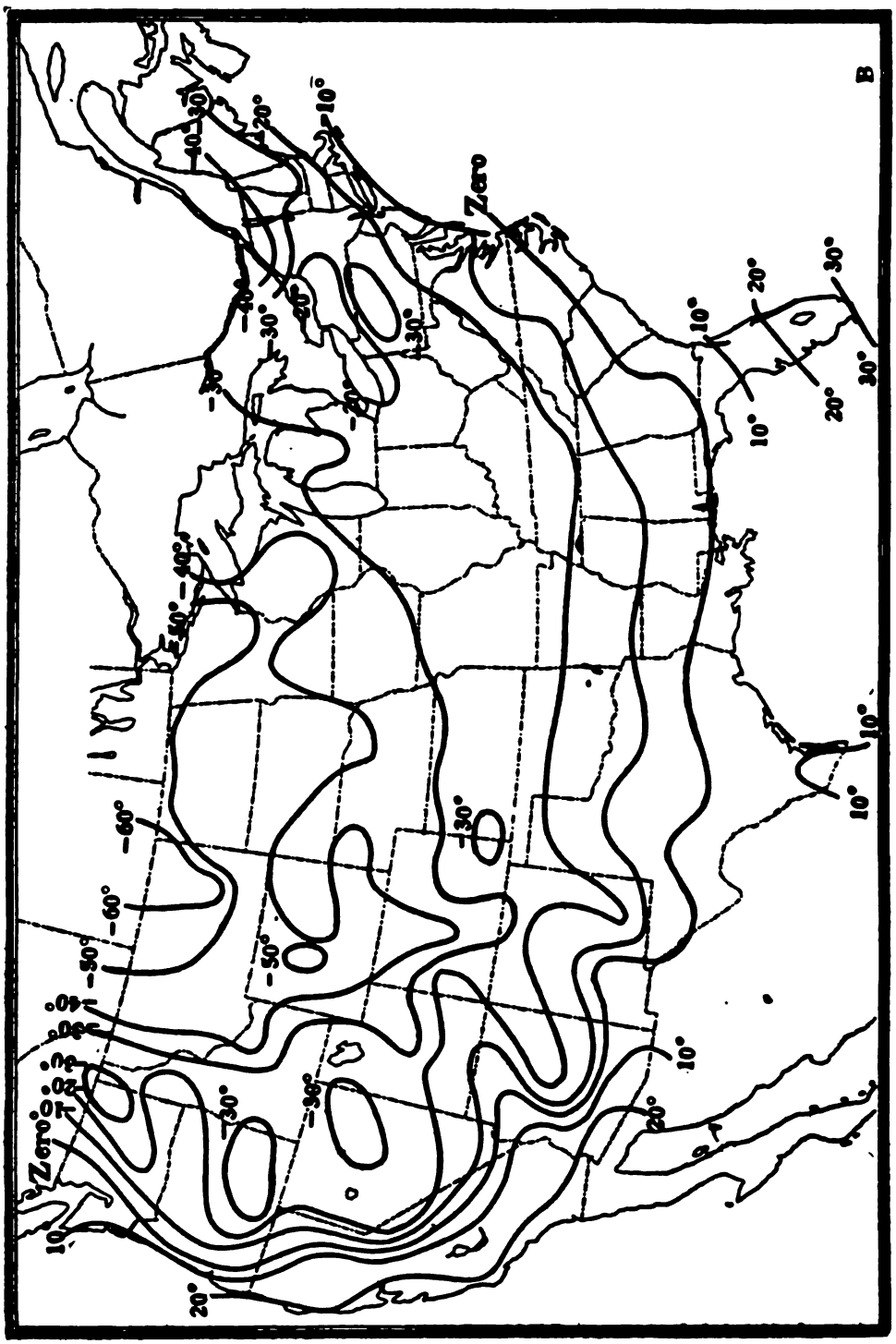

FIG. 64.—Absolute minimum temperatures in U. S., 1871–1912.

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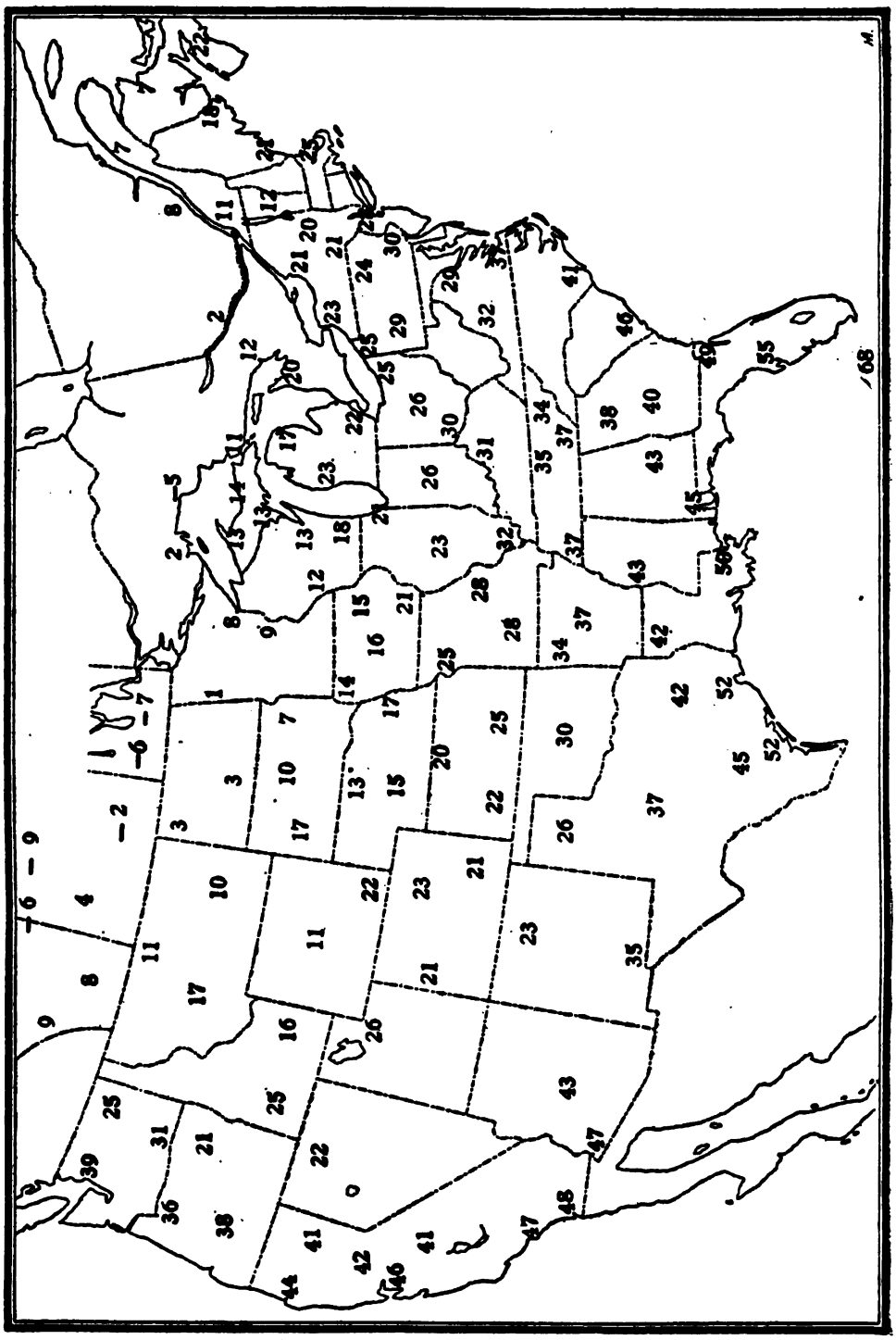

FIG. 65.—Normal 8 a. m. (75th meridian time) temperatures (degrees F.), third decade, January.

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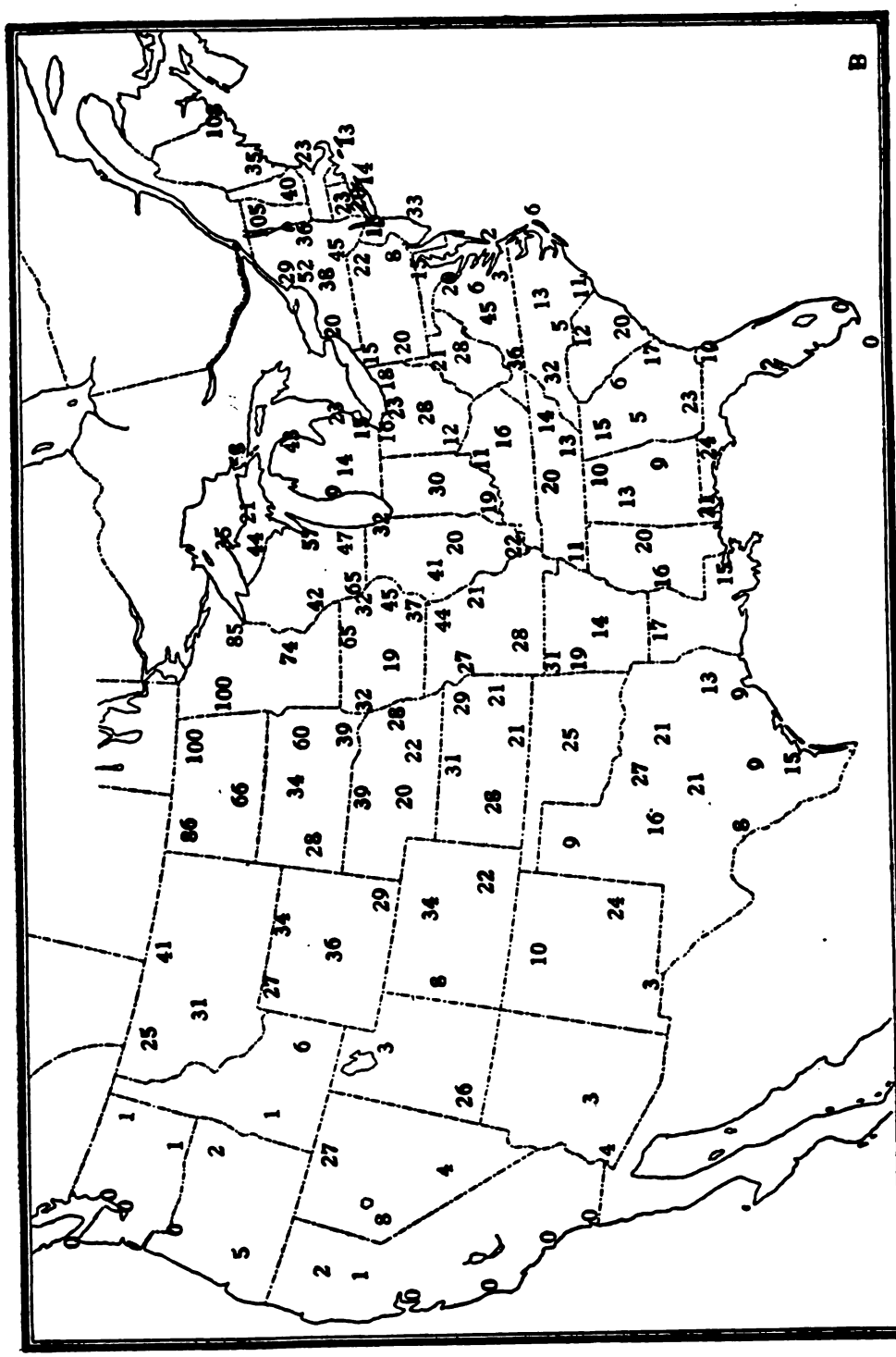

FIG. 68.—Number of cold waves, 1904–1914, inclusive.

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North have reference largely to possible damage to perishable goods in shipment and, on the eastern Rocky Mountain slope, to stock interests. As might be expected, the limiting temperatures in all sections are lower during December, January, and February than in the spring and autumn months, the purpose being to give warning of all sudden and marked falls in temperature that may be severe for the season.

The official definition of cold waves has been changed from time to time; thus until a few years ago the limiting temperatures to which the thermometer had to fall were considerably higher. It is obviously difficult to work out a thoroughly satisfactory scheme, but it is thought by forecasters of long experience that the present limiting temperatures serve the purpose admirably.

How cold waves occur.—Cold waves usually come suddenly, a decided fall in temperature occurring after a period with temperatures at or above the normal. There are, however, occasions when a very low temperature is reached by a slow fall covering a period of three days or more. A forecast of such conditions is not important, because they develop gradually and protection from damage can be more easily provided. A discussion of the forecasting of these slow falls in temperature belongs to the chapter on temperature changes.

Geographic distribution of cold waves.—The places where the minimum temperatures are the lowest (fig. 64) do not necessarily coincide with those where cold waves, so called, are most frequent, as shown by figure 66. For instance, the lowest absolute minima (fig. 64) are found in northeastern Montana, but cold waves are not so frequent there as in northeastern North Dakota (fig. 66). This is because many of the cold waves that advance from the Canadian Northwest take a southeasterly course over Manitoba and the Red River of the North Valley without affecting the northeastern slope of the Rockies, while all the cold waves that visit the latter section, including eastern Montana, later overspread North Dakota, Minnesota, and the sections lying to the east. The Red River of the North Valley, running between Minnesota and North Dakota northward into Manitoba, very seldom escapes a cold wave visiting the western portion of the country; and it is because of this that the normal minimum temperatures are lower there than in the sections farther west, although the extremes may not be as low.

Even with the great range in the requirements of verification, as noted previously, cold waves in the northern States east of the Rockies occur in large numbers, as compared with those in the Southern and Pacific Coast States. Verifications are seldom noted on the Pacific slope and in the Florida Peninsula south of Jacksonville. Of course, as stated before, freezing temperature occurs in the latter sections, but it is not usually reached in the required 24-hour fall of 16°,

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but almost always occurs on either the second or the third night of the cold wave.

Frequency of cold waves.—Figure 66 has been prepared to show the total number of cold waves in a 10-year period from the autumn of 1904 to the spring of 1914, inclusive, as verified by the 8 a. m. (seventy-fifth meridian time) observations. The number of cold waves recorded in northern New England is even greater than that in the Red River of the North Valley, Northfield, Vt., and Eastport, Me., having in the 10-year period 105 and 108, respectively, and Moorhead, Minn., 100. One reason why there is such an unusually large number in northern New England as compared with sections to the west and south is that many of the cold waves visiting it come from the Hudson Bay country in a southeasterly direction without affecting seriously the other districts, although places close to the frontier, like Canton, N. Y., and Sault Ste. Marie, Mich., are frequently within the track, as the figures in figure 66 show. Another reason is that the most frequented track of low-pressure areas is across northern New England and the lower St. Lawrence Valley, and near this path cold waves may be expected most frequently. This point will be referred to later.

During the period of 10 years not a single technical cold wave has occurred at the coast stations of California, Oregon, or Washington, while Red Bluff and Sacramento are the only two places in California west of the Sierras and Roseburg, Oreg., the only station west of the Cascade Range that have had any during that period—numbering one, two, and five, respectively. In the Florida Peninsula Tampa has had two in the period of 10 years, while none has occurred at Miami.

The above, of course, has reference only to instances when there was a fall in temperature in 24 hours sufficient to verify a cold-wave warning. Frequently, of course, the temperature falls lower than the required minimum, but not within the period of 24 hours. A notable case in point is the severe cold wave in California in January, 1913, the record minimum of 25° being observed at San Diego on the 7th, with readings as low as 28° on the 6th and 36° on the 5th, so that there was no technical verification. The notification of this low temperature was given through the frost warnings, as is usually the case in California and Florida.

There is no uniformity in the number shown in figure 66 for many reasons aside from those already given. If the requirements for verifications of cold waves were similar for all portions of the country and there were no water influences or pronounced differences in elevation, the number of recorded cold waves would doubtless decrease steadily from north to south. The simple fact that in the North the required limiting temperatures are only slightly below normal,

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while in the South these temperatures are far below the normal, is in itself sufficient to account for the unusually large number of recorded cold waves in the North as compared with those in the South, aside from the fact that storm movement with steep barometric gradients accompanied by marked changes in temperature are much more frequent in the North than in the South.

The differences in verifications, as shown by figures 62 and 63, for the various sections of the country are also responsible for many of the differences in the number of cold waves recorded in sections close to the dividing lines of the districts. For instance, Madison, with its 65 cold waves, has a larger number than either Milwaukee or La Crosse, between which Madison lies, or than Dubuque to the southwest and Green Bay to the northeast. This is doubtless because the line separating the zones of limiting temperature passes directly west of Madison. If the line passed east of Madison and zero were the limiting temperature required at Madison in the winter months, the number of recorded cold waves there would be much less and conform more closely to the records at other stations in the vicinity. Milwaukee, although in the same zone as Madison, is normally warmer in winter, and its number of recorded cold waves is therefore less. Cairo has likewise a larger number than Evansville, Ind., Louisville or Lexington, Ky., or Cincinnati, Ohio, only because, for verification purposes, Cairo happens to be included in a district not requiring so low a minimum temperature as the district in which the other stations are located. For the same reason, doubtless, a larger number of cold waves is recorded at Concordia, Kans., than in southern Nebraska, and at Oklahoma City, Okla., and Forth Worth, Tex., than at places directly to the north or south.

The influence of the Great Lakes on cold waves.—The influence of the Great Lakes on cold waves is shown by figure 66. The water of the Lakes is a decidedly modifying influence on cold waves, especially in the fall and the first part of the winter, and the cold must then be very severe in the northwest and barometric gradient quite steep in order to bring a cold wave across the Lakes and affect the Lower Michigan Peninsula. During such conditions a cold wave may occur at Chicago, while on the other side of the lake moderate temperatures may prevail. Not only is the number recorded much less at various points on the Great Lakes than at near-by places in the interior, but there is also a great variation in the number of verifications within the lake region itself, depending upon which side of the lake and how close to the water the station is located. The most striking differences are noted in the Lake Michigan region, the number on the west shore being five or six times as great as on the east shore. In a 10-year period, Milwaukee, Wis., has had 47 as compared with 9 at Grand

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Haven, the degree of the cold brought across the lake being materially reduced by the temperature of the water by the time it reaches the eastern shore. This lake influence affects, in a degree, the entire Lower Michigan Peninsula, but the effect is not so great in the interior and eastern sections as along the west shore. This fact is illustrated by the figures at Grand Haven as compared with those at Grand Rapids, Detroit, and Port Huron, with 14, 15, and 23 cold waves, respectively. So also in New York State, the number of cold waves is much greater in the interior than near the Lakes. For instance, Buffalo, Rochester, and Oswego, near the lake shore, had 20, 27, and 29 cold waves, respectively, while the interior stations of Ithaca, Binghamton, and Syracuse had 38, 45, and 52, respectively. In the Upper Michigan Peninsula there is a considerable difference between Houghton and Marquette, with 35 and 21, respectively, and a very great difference between the latter place and Sault Ste. Marie, where 58 were recorded, chiefly because Marquette is exposed directly to the water influence, while Houghton is a slight distance away from Lake Superior on Portage Lake; and Sault Ste. Marie is also located a short distance from Lake Superior on St. Marys River and its winds in a northwest cold wave do not blow directly off the lake. Moreover, at the latter station, many great falls in temperature are brought from Hudson Bay by a northeasterly wind or land wind instead of a northwest wind from the direction of Lake Superior.

The greater number of cold waves at Escanaba, 44, as compared with those at Marquette, 21, is because the main cold-wave wind, the northwest, at Escanaba, is off the land, while at Marquette it is directly off Lake Superior.

Because of pronounced lake influence during the fall and early winter, cold waves very rarely occur at points so situated on the Lakes that the prevailing wind is a lake wind. In fact it is not until January and February when the lake becomes at least partly frozen that cold waves are possible at these places. In the month of December, while the temperature of the water is still above 32°, not a single cold wave was noted during the period of 10 years at Grand Haven and only 1 at Grand Rapids, as compared with 6 at Milwaukee on the other side of the lake. Of course it can be readily understood that with a lake wind the temperature will not fall to 10° or even much below the freezing point (32°).

Influence of thermometer exposure.—Another reason for the lack of uniformity in the recorded number of cold waves in the various sections of the country is the great difference in the exposure of the thermometers. For instance, stations located in the country where radiation is free at night will show a much greater number of recorded cold waves than city stations. During cloudy weather, which

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usually precedes a cold wave, the minimum temperature is likely to be as high in the country as in the city, but with the coming of cold weather the sky clears, and the temperature falls to a much lower point at country stations, because of the freer radiation. Peoria, with the station located in its suburbs and a sod exposure for the thermometers, had, during the 10-year yeriod, 41 cold waves, as compared with 32 at Chicago. Peoria had a larger number than Chicago, not only because of the location of its station in the country, but also because it is away from the Great Lakes. Cold waves occasionally fail at Chicago because of a shifting of the wind from northwest to a northeasterly lake wind. Charles City, with an exposure in the country, had 65 cold waves, which far exceed the number credited to any other station in Iowa. So also has Meridian, Miss., a much larger number than Vicksburg to the west and Montgomery to the east.

Effect of variation in verification in different sections.—While the number of recorded cold waves at Mobile, Pensacola, and Thomasville is much greater than at other places directly to the north, this is doubtless because of the difference in verification, and, at Thomasville, Ga., also to sod exposure of the thermometer; but the number at these places is even greater than at cities farther west, as at New Orleans, because many of the cold waves moving southeast often affect these three cities without visiting New Orleans. As a rule, a reason can be found for the great variation in the figures in various parts of the country, although possibly in some cases it is not readily apparent.

Influence of topography and proximity to ocean.—Marked falls in temperature usually are produced by a HIGH following the movement of a well-marked LOW and with a steep barometric gradient between the two. As these conditions prevail much more frequently in the North than in the South, changes in temperature in the North, as stated before, are far more pronounced. The Pacific Coast States are in a class by themselves, as the temperature there is largely governed by the winds from the Pacific, which practically prevent cold waves, even in the extreme northern portion. In the Plateau, although very low minima sometimes occur as shown by figure 64, cold waves are infrequent. However, a large number has been recorded during the 10-year period at Winnemucca, Nev., and at Modena, Utah, 27 and 26, respectively, as shown by figure 66. At Winnemucca the winter minima are lower than at other stations in that section, and doubtless they are relatively low at Modena, although as yet no normals have been computed for this station because of its short record. (Fig. 65.)

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Brandenburg states as follows regarding the cold waves at Modena and Winnemucca:

My observation is that the greater number of cold waves occurs where the greater number of LOWS occurs. The topography of the middle and southern plateau region is such that LOWS that form in the vicinity (of which there are a large number some winters) and those that come from the South Pacific coast region almost invariably pass through Modena and Flagstaff. LOWS in these places if they move at all generally move rapidly, making the reaction in temperature pronounced. In most instances the cold that follows the passage of a LOW in the Plateau region is not the cold of translation, but is the result of the intense loss of heat by radiation at night that is common to the elevated arid region. A snow covering adds largely to the fall in temperature.

The number of LOWS that pass through Winnemucca is perhaps fewer than the number at Modena, but the deficiency is more than made up by the number of northern LOWS that loop southward, and sharp changes in temperature occur, even though the true centers are far to the north.[1]

Willson, of San Francisco, writes as follows regarding these differences in the Plateau region:

It is my opinion that the radical changes at Winnemucca are due mainly to topography. The mountain ranges to the north are low and have a decided north and south trend, which facilitates the southward movement of cold air from the north. The same conditions appear to hold good for Modena, but Reno, Boise, and Tonopah are surrounded by broken ranges and spurs, which retard the flow of air from the north. Both Reno and Boise are especially well protected by mountains and have good drainage.

It appears from the above extracts that frequency of cold waves at Winnemucca and Modena, as compared with other points in the Plateau region, is due to variation in topography (including air drainage), and to proximity to storm tracks, aside from the effect of altitude.

At the mountain stations in the East, where the night temperatures are comparatively low because of the altitude, the number of cold waves is much greater than at adjacent points in the low country, according to the figures at Elkins, Wytheville, Asheville, and Lynchburg, as compared with Washington, Raleigh, and Columbia.

The figures in figure 66 show the number of cold-wave verifications for the 10-year period for the 24 hours ending at 8 a. m. only (seventy-fifth meridian time). Occasionally the required verifications have been noted at some other hour, but these are not included on the chart. Moreover, these excepted are not important as a rule. The figures suffice to show the relative frequency of cold waves in various portions of the country, as the data are comparable.

Movement of cold waves from Canadian Northwest.—Garriott says in Bulletin P, "Cold Waves and Frosts in the United States":

[1] The ordinary day to day nonperiodic changes of temperature at Winnemucca are frequent and pronounced, due doubtless to local topography and intense nocturnal radiation as suggested.—Editor.

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East of the Rocky Mountains the principal track of the American winter LOWS lies south of the fiftieth parallel of latitude, and the mechanical action of energetic LOWS that follow this track disturbs the North American cold belt and draws southward, and probably downward in their wake, masses of cold air that constitute the cold waves of the United States.

The supposition has been advanced that the North American cold belt may be reinforced by air masses that advance via the Arctic Ocean from Siberia; a more probable supposition, however, is that the cold of the northern interior of the American Continent is due to air that flows over that region from the northern Rocky Mountain ranges, where its moisture has been precipitated. The result of a loss of moisture in the passage of the mountains leaves this air clear and dry, and promotes the process of heat radiation that continues during the passage of the air over the Canadian Northwest. It seems, therefore, that slow or stagnant conditions of the atmosphere over the Canadian Northwest are favorable to one of the conditions (that are represented by accumulations of great air masses or areas of high barometer of great magnitude) that produce cold waves in the United States. The other necessary condition is the passage or the development of an area of low barometric pressure along or near the southern margin of the cold-air mass or belt, within the western quadrants of which the cyclonic circulation will produce powerful air currents from the north.

It is doubtless true that many cold waves are developed in the Canadian Northwest east of the Rockies through rapid radiation of heat over a snow-covered surface during the long winter nights. Many instances have been observed of this development in Saskatchewan and Alberta, and occasionally even within portions of the United States lying immediately to the south, when snow lay on the ground.

Once the conditions of cold have been established all that is necessary to insure a transfer of it southward and eastward is the development of a LOW in those directions. This will produce a drainage of cold air from the north, with accompanying north to northwest winds. Brandenburg says: "the greater number of cold waves occurs where the greater number of LOWS occurs," and we find this to be a fact, as the LOWS move eastward across the northern frontier most frequently where cold waves are the most prevalent. The actual cold is generally transferred by the strong winds due to the barometric gradient prevailing between the LOW and the HIGH, but the intensity usually gradually diminishes as the wave advances, because it passes over regions having a higher temperature. Local radiation is important, and in the elevated sections of the Plateau region it is the principal factor. Comparatively low temperatures sometimes occur in that section in a HIGH which has moved in from the Pacific coast following a LOW, but rarely do they reach the proportions of a cold wave, unless the HIGH is reinforced by another HIGH moving southward from British Columbia.[1]

In a winter marked by severe cold the LOWS generally take the southerly course and are followed in turn by well-defined HIGHS from

[1] See the discussion on reinforced HIGHS, p. 131.—Editor.

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the northwest, while in warm winters there is a succession of LOWS moving eastward over the northern frontier, and the HIGHS in the rear instead of coming from the British Northwest approach from the middle Rockies or at least no farther north than the frontier.

Various types of cold waves.—Having touched upon the general causes of cold waves and their relative frequency in various portions of the United States, and the reasons for the great variation, it will now be proper to study the type maps, each of which presents special conditions. There is a similarity between some of these types and yet often a slight apparent difference is responsible for a cold wave moving to one side or the other of its usual track.

A rise in pressure in the northwest and a fall to the south or southeast are indications of the approach of lower temperatures, and where the pressure changes are decided marked changes in temperature will ensue, although as yet no cold weather may have appeared in the northwest.

When a HIGH is present over the South Atlantic States, the movement of cold waves eastward is generally retarded and the cold seldom seriously affects the Atlantic States, even those in the north. (Jan. 12–14, 1911; Jan. 26, 1911; Jan. 5–7, 1913; Mar. 26–27, 1914.)

If the barometer is low over the South Atlantic States, the cold wave is invariably far-reaching and low temperatures and frost ensue usually as far south as Florida.

The cold wave which affects most seriously the Middle West is one which is preceded by a crescent-shaped LOW reaching from Minnesota or Lake Superior southwestward to the middle Rockies, the HIGH at the same time being centered over the northern Rockies. The southwest end of the trough is forced eastward by the HIGH, as the latter advances, and the cold rapidly pushes down from the northwest. (Nov. 11, 1911; Jan. 5–8, 1913; Jan. 10–12, 1913; Feb. 1–3, 1907; Dec. 31, 1910–Jan. 1, 1911. See maps of Nov. 10, 11, 1911, reproduced as figs. 67 and 68 to illustrate this type.)

A type of continued cold is that in which there is a redevelopment of a HIGH over the northern Rocky Mountain region with falling temperature, the principal LOW being centered over the eastern Lake region or North Atlantic States and a secondary depression over the central or southern Rocky Mountain region. These conditions present practically the same possibilities as the crescent-shaped LOW mentioned above, except that in this instance the initial temperatures in the Plains States are likely to be low, and the exchange of heat is then less than that which prevails in front of a crescent-shaped trough. (Jan. 4–5, 1912.)

The southwesterly trend of a trough, no matter where situated, is best adapted for inducing a flow of cold air from the Northwest, because in that case the cold in the Northwest moves directly south

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and southeast. As a general proposition it may be stated that the farther a trough extends southwesterly or westerly, the more sweeping will be the cold wave. Where there is no appreciable trough but merely circular isobars to the southward of the LOW center, as is occasionally noted when the LOW moves eastward over the northern Lake region, the effect of the cold wave is not felt southward to any great extent. Maps of March 5–6, 1913, to illustrate this type are reproduced as figures 69 and 70.

When a LOW is centered over Minnesota or eastern Manitoba, with the isobars in its rear as far back as Saskatchewan, turned to the northeast and crowded close together and accompanying strong wind velocities, a cold wave will immediately follow and a HIGH will cover the Dakotas and Minnesota in the ensuing 12 to 24 hours. (Feb. 3–4, 1906; Dec. 10–11, 1910; Jan. 30, 1913.) Maps of February 3–4, 1906, illustrate this type. (See figs. 71 and 72.)

When a HIGH with severe cold prevails in the Canadian Northwest and the isobars run in an east-west or northeast-southwest direction south of the center of the HIGH, the wind direction is usually northeast or east in the northern portions of Montana and North Dakota, and while the cold may draw southward over some of the frontier States, the cold wave will not become general, but will remain in the north until a LOW moves in from the Pacific over the middle Rockies, after which the northwest HIGH may swing around and take a southeasterly course. (Feb. 4–7, 1914; Mar. 19–21, 1912; Mar. 20–Apr. 2, 1908.) If the cold in the northwest is severe, however, and there is a pressure fall in the central valleys, the wave will move southward and be more or less general. (Dec. 24, 1914.)

In case the LOW is in the southwest and the HIGH in the northwest, and no portion of the LOW breaks off and moves east of the Mississippi, the HIGH does not advance southward materially, but rather moves eastward over the northern frontier with northeast winds blowing out of it and often with moderate temperature, the cold not being felt except in the frontier sections. (Feb. 25–26, 1907; Jan. 29–31, 1907.)

When a cold-wave HIGH is present in the British Northwest and there is a general low-pressure system covering the Pacific coast region, reaching in over the middle Rockies, the HIGH does not move southward, but the winds blow out of it in a northeasterly direction toward the low-pressure system. (Mar. 26–27, 1914; Jan. 20–21, 1913; Jan. 12–13, 1907.) Maps of January 12–13, 1907, are reproduced as figures 73 and 74, to illustrate this type.

When a cold-wave HIGH is advancing from the northwest and the greatest 12-hour rise in pressure appears over the Lake Superior region, the center of the HIGH will usually move to that point and

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cause northeasterly winds over the upper Lake region and upper Mississippi Valley and will not cause a cold wave in the southern portions of these sections. (Mar. 26, 1914; Jan. 11, 1911; Jan. 15, 1909; Feb. 4, 1906; Mar. 24, 1908.)

If the movement of the HIGH and the LOW is such as to cause the wind to shift to the north and northeast, the cold wave will not be general. Sometimes, with high pressure in the north and a LOW in the southwest, there is doubt as to the movements of these areas. If the LOW advances in an easterly direction more rapidly than the HIGH, a cold wave will ensue, but if the HIGH advances more rapidly than the LOW, northeast and north winds will prevail, and there will not be any decided fall in temperature.

In order to bring a cold wave to any point the distribution of pressure must be such as to cause the winds to blow from a north or west direction, and preferably from the northwest. Some cold waves, however, approach from a west to southwest direction in the Middle West when the LOW moves almost due north and the HIGH following passes southeastward. (Dec. 4–6, 1909; Nov. 30–Dec. 1, 1908.) Maps of December 5–6, 1909, are reproduced as figures 75 and 76, to illustrate the type.

Regardless of how severe the cold is in the northwest, it can not advance to any extent unless there is fairly steep barometric gradient in its front, with accompanying strong winds. (Dec. 4, 1908; Jan. 3, 1907; Jan. 14, 1907.)

When a LOW in front of a cold wave is deepening, severe cold ensues because of the increasing winds and consequent stronger inflow of the cold; when the LOW is losing intensity and is filling up, the cold following is modified decidedly.

A slow-moving LOW is seldom followed by severe cold, regardless of where the LOW is situated, as the movement of a cold wave is usually rapid. If the cold wave is retarded, it is likely to lose its intensity and be followed in the northwest by a LOW before any great falls in temperature have occurred outside of the more northern districts. (Jan. 21–23, 1896; Feb. 8–10, 1909; Feb. 14–17, 1909; Jan. 20–23, 1906.)

For a cold wave to sweep the mountain States of Wyoming and Colorado, the center of the HIGH to the north must be no farther east than the Rocky Mountain Divide, and a LOW must lie over the mountains to the south, with its axis in an east-west or northeast-southwest direction. (Feb. 28–29, 1912; Jan. 4–5, 1913; Jan. 1, 1910; Dec. 31, 1910.) Maps of January 4–8, 1913, are reproduced as figures 77–81, to illustrate this type.

When a cold wave is preceded by a LOW, in which heavy rains are falling, especially when the disturbance is central over the middle or

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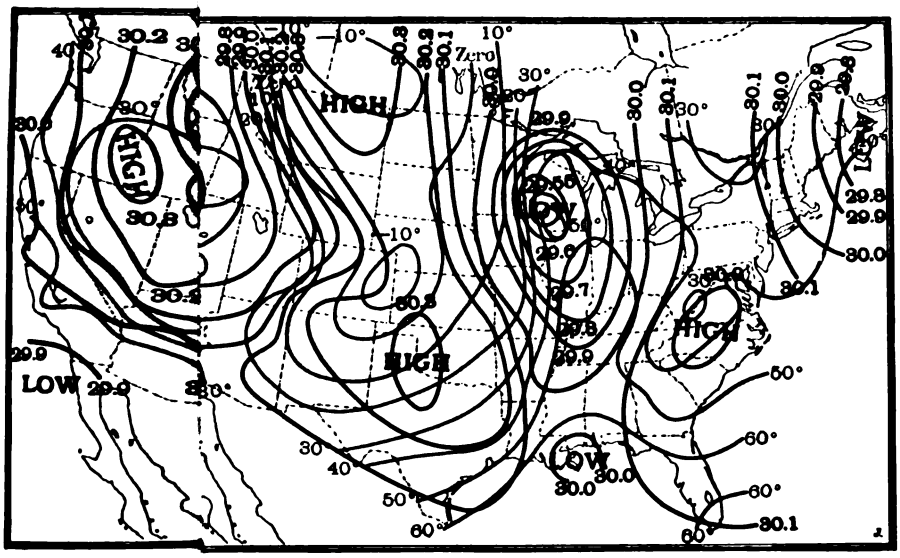

Fig. 75.—December 5, 1909.

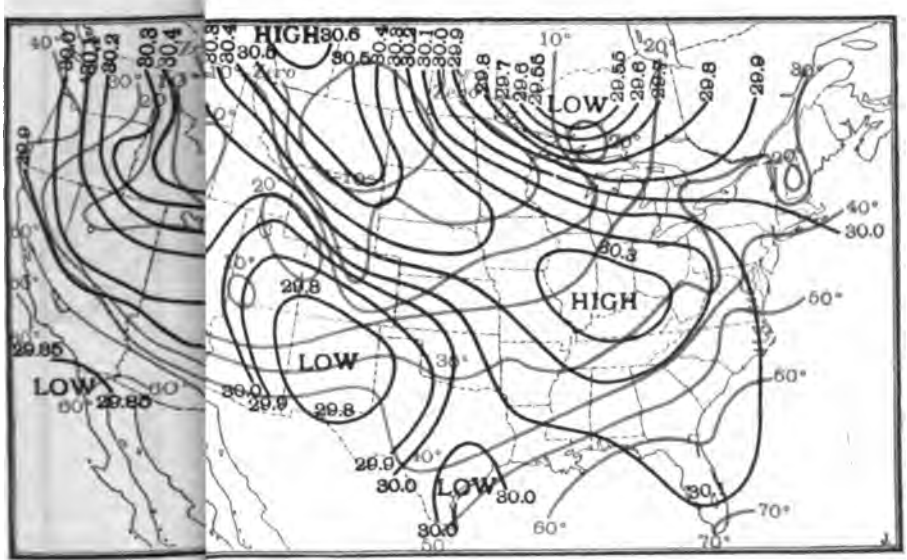

Fig. 76.—December 6, 1909.

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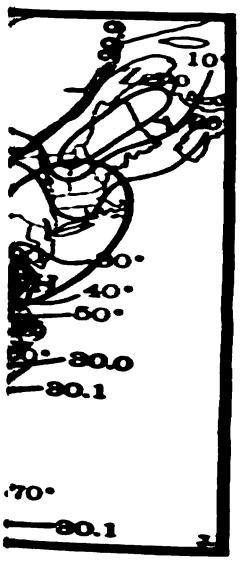

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lower Mississippi Valley, the cold wave is not likely to be general and its movement is usually retarded. Generally in this case an extensive and slow-moving HIGH is present in the east in front of the LOW and serves to retard the easterly movement of conditions farther west. (Feb. 26–27, 1913; Mar. 24–26, 1913; Jan. 6, 7, and 8, 1913; see figs. 79, 80, and 81.)

When a cold-wave HIGH, located west of the northern Rockies, moves southward over the Pacific coast districts, its force is seldom severe on the east side of the Rockies, unless there is a development of a LOW in the east to draw the cold down over the Plains States, as in the maps of February 12–13, 1905. (Jan. 4–6, 1910; Feb. 12–13, 1905; Dec. 17–19, 1908; Dec. 31, 1905–Jan. 4, 1906.) Maps of December 18–19, 1908, are reproduced as figures Nos. 82 and 83 to illustrate types where severe cold advances south over the Pacific coast region and sections east of the Rockies.

If a northwest cold wave is followed immediately by a well-marked LOW directly to the west, the cold-wave conditions are not usually evident west of the Missouri Valley, that section by the following morning being under the influence of the western LOW. (Jan. 23–24, 1906; Feb. 24–25, 1906.)

When a HIGH of considerable magnitude covers the western plateau region, there is little opportunity for a general cold wave to overspread the Plains States and central valleys. If a cold wave under such circumstances does appear in Alberta, a tongue of low pressure extends in a southeasterly direction from the northern Rockies between the cold-wave HIGH and the plateau HIGH, so that the cold is not felt to any extent on the eastern Rocky Mountain slope. (Feb. 1–2, 1906; Feb. 20–21, 1907; Jan. 21–22, 1907.)

When a LOW in the west or northwest follows rapidly a cold wave, the temperature in the cold wave will ordinarily not fall to a low point, as the wind in the HIGH is likely to shift quickly to the east, southeast, or south.

Aside from the modifying influence of latitude, a cold wave usually loses some of its intensity with gradually diminishing barometric gradient in its front, as the wave advances, largely because the LOW in front of a cold wave ordinarily moves much faster than the HIGH and the LOW moves to the northeast or east while the HIGH moves generally southeasterly. It is because of these modifying conditions that cold waves which may be severe in the Middle West are seldom felt intensely in the Atlantic States unless the pressure has been low on the southern coast. The barometric gradient, however, always increases, either when the LOW deepens, as stated previously, or because of increasing pressure in the HIGH, and such conditions insure very low temperatures within the path of the cold wave.

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The conditions which sometimes cause the most severe cold waves in New England and the northern portion of the Middle Atlantic States are those which move southeastward from the Hudson Bay region, usually reaching southward over northern Lake Superior at the same time that a LOW is present off the north Atlantic coast. (Feb. 5–6, 1906; Jan. 12–14, 1914; Jan. 4–5, 1904; Feb. 8–9, 1908; Feb. 22–23, 1907.) Maps of January 13–14, 1914, are reproduced as figures 84 and 85, to illustrate this type.

When the cold in the northwest is accompanied by a HIGH of 30.7 inches or more, the area usually moves directly down the eastern slope of the Rockies in a direction between southeast and south, to Texas, and then eastward across the Gulf region to the South Atlantic coast. When the pressure is as high as 30.8 inches, regardless of other conditions, this movement is almost always noted. Such a HIGH scarcely ever moves eastward over the district north of Lake Superior as some other HIGHS do, even though the greatest 12-hour pressure rise is found in that section. Following the movement of the HIGH southward, a marked rise in temperature immediately overspreads the northwest. These HIGHS, of course, usually steadily decrease in magnitude, as they move southward, as stated previously. (Feb. 3–4, 1912; Jan. 14–15, 1905; Nov. 12–14, 1908; Dec. 8–9, 1898; Dec. 26, 1894; Jan. 22, 1897; exception to above, Mar. 1–2, 1896.) Maps of November 12–14, 1908, are reproduced as figures 86, 87, and 88, to illustrate this type.

When the trend of the isobars over the Middle and Southern States is such as to promise northeasterly winds over the Florida peninsula, the same effect is produced as over the Lake region with like conditions, and no pronounced cold in Florida ensues. It takes a north to northwest wind to bring the cold there. This type is so common that examples are not necessary, and it occurs when the HIGH does not extend southward into the Gulf, but rather north of the Gulf coast, so that the HIGH eventually passes eastward north of the Florida peninsula.

When in a northwest cold wave there is snow and persistent cloudy weather severe cold will not usually follow. The clearing up of the weather in the HIGH itself, however, will cause still further falls in temperature there, sometimes reaching the proportions of a cold wave, although no marked barometric gradient is evident. This is especially noticeable when there is snow on the ground. (Feb. 10–11, 1913; Feb. 13–14, 1913.)

When the center of a HIGH is as far east as Manitoba, it usually does not move down over the States lying to the south, but rather across the northern Lakes. (Jan. 20–21, 1912; Jan. 11, 1911; Jan. 14–16, 1909; Jan. 28–29, 1908; Feb. 6–8, 1908; Mar. 5–6, 1907.)

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FIG. 88

FIG. 8

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There are marked exceptions to this case. When there is a deep LOW over the middle Western States, reaching back to the Rockies, and the cold wave in the northwest is severe and the pressure excessive, the HIGH will extend back westward and swing southward over the eastern slope of the Rockies. (Feb. 22–23, 1914; Feb. 14–17, 1910; Feb. 9–13, 1905.) Sometimes under these conditions the LOW is divided by the southerly movement of the HIGH, one depression being east of the Mississippi and the other in the middle or southern Rocky Mountain region. (Feb. 25–26, 1913; Mar. 20–22, 1913; Dec. 29–31, 1911.) If the gradient diminishes between the HIGH and the eastern LOW, the HIGH will not move due eastward but will gradually settle toward the southeast and south and not cause severe cold weather in eastern sections. (Feb. 25–26, 1913; Feb. 14–17, 1910; Dec. 29–31, 1911.)

If the HIGH advances from the northwest, dividing a single depression in two, and causing a well-marked cold wave as far south as Nebraska, the cold wave may then be expected to swing eastward over the Mississippi Valley and the Lake region, provided there is sufficient gradient between the HIGH and the LOW. (Mar. 20–21, 1913; Jan. 1–4, 1910; Jan. 5–7, 1909; Jan. 14–16, 1907.) But when the cold does not reach as far south as Nebraska, only the northern portion of the Lake region will be affected to any extent in the movement of the HIGH.

When a cold wave, even though very severe, is centered in the Canadian Northwest, and at the same time the barometer is low and the temperature high over an unusually large area to the southward and eastward, without definite storm development, the effect of the cold wave is usually not felt to any marked extent in any of the Northwestern States. The cold wave loses its intensity and often is completely broken up when opposed by a very wide area of high temperature. (Feb. 8–9, 1909; Feb. 28, 1907; Mar. 24–26, 1914; Feb. 12–17, 1909; Jan. 27, 1914; Dec. 4, 1908.) Maps of February 8–9, 1909, are reproduced as figures 89 and 90, to illustrate this type.

If a plateau HIGH begins to disintegrate and the pressure falls there, with the barometer steadily rising at Edmonton and with falling temperature, a cold wave HIGH will be found in Alberta within the next 24 hours that is likely to sweep the Middle West. (Dec. 29–30, 1908; Jan. 23–24, 1907; Jan. 28–29, 1914.)

Frequently in winter a HIGH in the form of a ridge, with its center over Alberta and a cold wave general throughout the north Central States, reaches southeast over the eastern slope of the Rockies to Texas. At the same time there is one LOW over the east or east Central States and another on the Pacific coast. This HIGH does not move east but frequently will remain for days in the same position,

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sometimes even pushing farther west and redeveloping. With its high pressure and low temperature it blocks the Pacific LOW until the latter is dissipated or pushed out into the Pacific. Under these conditions the winds will be continuously from a westerly direction over the north Central States with fair weather. After the temperature has fallen in the central valleys and the Lake region, it remains cold or moderately so until the HIGH advances or is broken up. (Feb. 3–8, 1913; Feb. 9–15, 1907.) Maps of February 3–6, 1913, are reproduced as figures 91, 92, 93, and 94, to illustrate the beginning of a series of LOWS and HIGHS of this type.[1]

Sometimes a ridge of high pressure will block a LOW that is centered directly west of the Rockies and finally force it back to the Pacific coast. In this case as well as in the one immediately preceding, the HIGH will finally move down to the Gulf region. (Feb. 20–23, 1911.)

Frequently in winter a LOW will develop over Manitoba and move directly southeast over the Lake region, followed by a well-marked cold wave sweeping the upper Mississippi Valley and the greater portion of the Lake region. These conditions will move rapidly and will be attended by precipitation of short duration. (See figs. 95 and 96 as illustrating this type; also Mar. 4–6, 1913; Jan. 31–Feb. 2, 1912; Dec. 6–8, 1912.)

Special conditions affecting the movement of cold waves.—The movement of cold-wave conditions is often checked by other conditions 2,000 or 3,000 miles to the eastward, generally in the shape of an immense HIGH over the Atlantic Ocean or the Atlantic Coast States, which for some reason is held stationary and blocks for a time the movement of all barometric formations in this country.

As stated before, a cold wave of the most sweeping character from the Rocky Mountains eastward ensues when the HIGH is centered over the northern Rocky Mountain region and a trough of low barometer extends in crescent shape from the Great Lakes southwest to and beyond the middle Rockies. Sometimes the western end of this trough is forced rapidly southeastward and the northern end temporarily remains stationary, the trough, as a consequence, extending from north to south and moving eastward in that form. At other times the western end of the trough is forced directly southward over Texas; in such cases the cold wave sweeps the entire State to the Gulf and overspreads the central and eastern portions of the country. The cold-wave HIGH then is usually of great magnitude, but with gradually diminishing size as it advances southward. After reaching the west Gulf coast it moves eastward to the South Atlantic coast, following a well-marked depression in its

[1] See also Chap V, p. 120, where practically the same type is discussed.—Editor.

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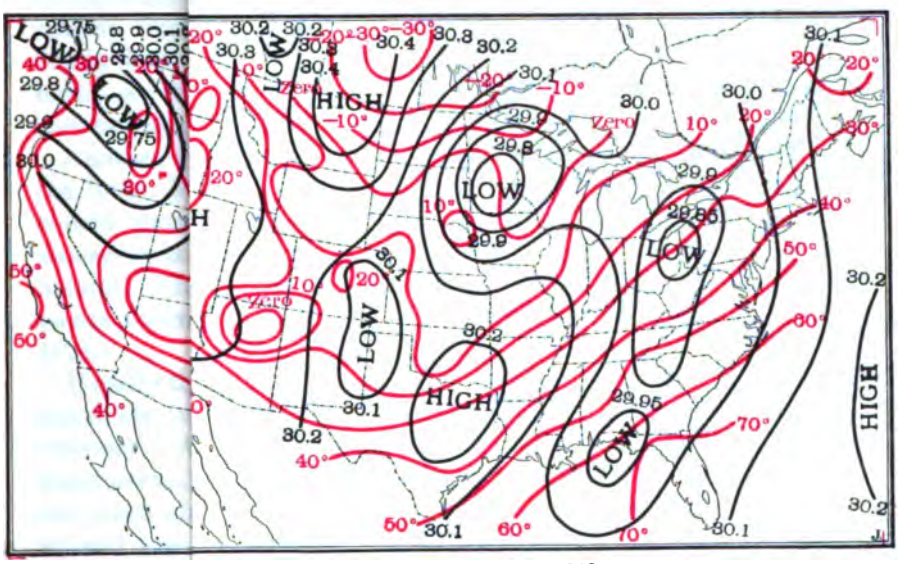

FIG. 95.—March 1, 1913.

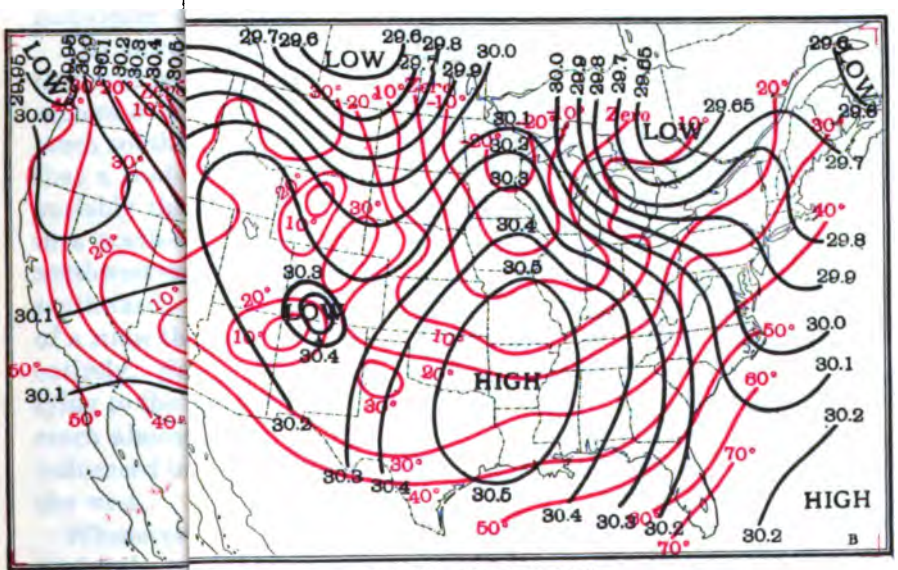

FIG. 96.—March 2, 1913.

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front. A similar distribution of pressure ensues, without the so-called crescent-shaped trough as a factor, with a LOW over the North-central States and another in the southwest, which deepens and finally becomes the chief disturbance, drawing the HIGH from the north, as the LOW itself advances eastward and joins the northern LOW by means of a trough. (Dec. 12–14, 1915.)

Another type which brings cold waves to the States lying between the lower Mississippi River and the Rocky Mountains occurs when a cold wave is present in the Northwest and a north-Pacific LOW moves southeastward across the middle Rockies to the Texas panhandle. The disturbance then recurves northeastward and finally passes down the St. Lawrence Valley. (Jan. 1–3. 1911; Feb. 5–7, 1914.)

Usually the greater the pressure in the HIGH, other conditions being equal, the lower the temperature will fall and the slower will be its recovery. At times, especially in the spring when cold-wave conditions prevail in North Dakota and western Minnesota with a HIGH not much above normal (30 inches), the cold will be quickly broken up and will not be felt to any extent farther east.

While cold waves generally come from the Canadian Northwest, they occasionally develop within the limits of the northwestern portion of the United States east of the Rocky Mountains, but only in midwinter when the ground is covered with snow.

The more southerly the movement of a HIGH the greater the area that will be covered by the cold; HIGHS moving eastward with their centers over the northern frontier do not usually cause cold waves much south of that line. As a general proposition it may be stated that a cold-wave HIGH moves southeastward, and this is almost invariably the case when the trough of low pressure in front extends in a north-south direction. When the trough extends westward or southwestward, the HIGH in the northwest usually pushes directly southward, but it is because of the usual southeasterly movement of a HIGH that districts lying to the south of a cold wave often escape entirely. Sometimes the eastern slope of the Rockies and the sections lying to the west only may escape, while at other times this area may reach almost to the Missouri River. The movement of the HIGH is influenced in this case, as in others, by the distribution of pressure in the west.

Whenever, in the progress of a cold wave over the middle Western States the temperature in its front rises to an abnormally high point, although the fall in temperature may be very pronounced in the northwest, the minimum does not reach as low a point at any particular place farther east as it would had the temperature not been so high. For instance, if the temperature at Chicago in front of a cold wave is 50° or more before it begins to fall, it will not go nearly so

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low as if the initial temperature had been no higher than freezing (32°). This is because in the exchange which takes place between the air of the cold wave and that which it displaces the higher the temperature of the latter the greater will be the amount of heat communicated to the cold wave; and also because the cold wave is moving across a region that has been warm. The departures from the normal temperature in the various sections that are to be affected must be taken into consideration.

When the humidity is high over an area in advance of a cold wave, the fall in temperature will be retarded and the ensuing minima modified decidedly because of the fact that radiation or loss of heat through humid air is slow, as compared with the radiation of heat through dry air.

When a cold wave threatens any point, a cloudy sky which prevents the temperature from rising during the day is much more favorable for the verification than when the day is clear, because in that case, the journey to the verifying point will not be so long as if a comparatively high maximum were reached.

So also are the chances for verification much better if the ensuing night is clear so that radiation may be free. A cold-wave warning will ordinarily fail of verification unless the night is clear.

The time of day when a cold wave strikes any particular section is important in connection with the verification. If the crest of the wave does not reach the place until after the usual time of minimum temperature, after 7 a. m. for instance, the warning is not so likely to be verified as if the crest arrived earlier, because of the diurnal rise in temperature. A verification is much more likely at 8 a. m. than at 8 p. m. because the normal p. m. temperatures are about 9° higher in the wintertime. These facts, of course, are not important when the anticipated cold is severe.

During impending cold-wave conditions, when the barometer rises rapidly at any particular place that is threatened, without a relatively rapid fall in temperature, the prospects of verification are poor. With each rise of a tenth of an inch in pressure there must be a fall in temperature of 3° or 4° in order that the required fall may occur in 24 hours. Otherwise the highest point in pressure will soon be reached with the temperature still far above the point required to verify.

Where there is a difference of 1 inch in gradient between the northwest HIGH and the eastern LOW the cold is likely to be severe, the wind in that case being sufficiently strong to transport the cold from the northwest. Roughly, at least 0.50 inch should be the difference in pressure between North Dakota and Lake Michigan and another half an inch between Lake Michigan and New England.

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A cold wave seldom lasts longer than two or three days, except in the northwestern part of the country east of the Rockies; any cold wave that occurs after the middle of February, when the sun is becoming higher and higher and the nights markedly shorter, is almost always of short duration. The great frequency of cold waves in the North as compared with those in the South is partly because the winter nights are so much longer there than in the South. The winter night averages about an hour longer at Chicago and nearly two hours longer at Winnipeg than at New Orleans.

After the middle of February it is more difficult to secure a verification of a cold-wave warning, as the day temperatures in the HIGH are becoming higher and higher. As the season advances this fact becomes one of the greatest importance. In considering the matter of cold waves we have to estimate how much the temperature in the HIGH will rise during the day as it advances farther and farther eastward.

Charts used in forecasting cold waves.—The "A" chart and the pressure-change chart are those upon which the forecaster must depend in forecasting cold waves. If the pressure in a cold HIGH in the Northwest continues to rise, the cold will intensify.

The direction of movement of HIGHS and LOWS is indicated by the pressure changes, and the movement of cold waves is especially indicated by the 12-hour changes. Frequently the greatest 12-hour rise in pressure, as shown by the barometer-change chart, indicates the point to which the center of the HIGH will move within the next 12 hours, although less frequently the greatest fall in pressure in 12 hours indicates the future position of the LOW. This rule is not infallible and there are marked exceptions to it. When there is a very deep LOW moving across the country, it is usually followed by a rapid rise in pressure, and in that case the center of the rise does not indicate that the HIGH will move to that point, the place of previous lowest pressure often merely filling up.

A cold wave will usually occur only in the districts to the south or southeast of the point of greatest 12-hour rise in pressure and ordinarily east of the 12-hour no-change line on the pressure map, the area covered varying with the rate of progress of the HIGH and the LOW. There is an exception to this rule which is often noted in the Northwest and especially in the Dakotas and eastern Montana in that the redevelopment[1] of a HIGH or the clearing up of cloudy conditions will often result in a cold wave, as stated previously.

A rise in pressure of 0.50 inch in Alberta in 12 hours following a northwest LOW is usually an indication of a development of a cold wave in the Northwest regardless of other conditions.

[1] See also the discussion of reinforced HIGHS, Chap. V.—Editor.

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With the barometer falling in front of a cold wave and the greatest fall well to the south, whether in central or eastern sections, the ensuing cold is sure to be pronounced and general.

The pressure change chart is of the highest importance in forecasting cold waves, and it must be studied carefully. The chart will often show impending falls in temperature, not apparent upon the weather map, commonly called the "A" chart. Should the temperature be low in the northwest, there is need of giving especial attention to the changes, both 2-hour and 12-hour, on the pressure chart. Whether the pressure changes be large or small, the chart will usually indicate the probable distribution of pressure 12 and 24 hours later, and the resulting temperature changes.

The next chart of importance in forecasting cold waves is the normal temperature chart or a chart showing the departures of the current temperature from the normal for that day. When the temperature, falling to a point only slightly below the normal will verify a warning, the chances of verification, aside from other conditions, are favorable. When the temperature is already below the normal, verification is not obtained except as a result of severe conditions. It should be realized that the midwinter normal minima in Manitoba and Saskatchewan are from —2° to —9° below zero F., and in Alberta, from 3° to 9° above. A HIGH must therefore have temperatures lower than these during that period in order to insure a cold wave in any particular part of the United States. Of course, if the temperature is far below the normal in the northwest HIGH, the prospects of severe cold in its advance are good. However, some cold waves upon their first appearance in the British Northwest are not accompanied by extremely low temperatures, but when conditions are active—rapidly rising pressure in the Northwest and falling to the Southeast—the temperature will continue to fall until severe cold has finally developed.

The temperature-change chart must be used with caution, and we must be certain that from the 24-hour changes in temperature we can properly interpret current conditions. The 12-hour changes in temperature with allowance made for the difference in the normal readings in that period are much more valuable. If, however, there is a 24-hour fall of from 20° to 40° in the British Northwest, it is ordinarily probable that a similar change will be felt immediately to the south and east, but we must in all cases allow for temporary changes in temperature that may have intervened during the last 24 hours. Sometimes a great fall is noted in the Northwest, but pressure conditions in the meantime may have so changed as to prevent the transfer of the cold to other sections. The temperature-change map can be satisfactorily used only as supplementary to the "A" chart and the pressure-change chart.

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In the foregoing paragraphs the various types of cold waves and the conditions which affect their development and movement have been discussed. It is obvious that the degree of cold recorded in a cold wave depends upon the intensity of the cold in the HIGH and the temperature in the LOW in front of the HIGH, the magnitude of the HIGH, the barometric gradient between the HIGH and the LOW and the consequent wind force, the direction of movement of the HIGH and also the LOW or LOWS which it is following, the general character of the sky, the humidity, whether there is snow on the ground, and the season of the year; in a word, all the atmospheric conditions, sometimes even within an area of 3,000 or 4,000 miles or more.

Following are statements from the various district forecasters containing their special reports regarding the forecasting of cold waves in their districts.

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COLD WAVES IN NEW ENGLAND.

By JOHN W. SMITH, District Forecaster.

Cold waves in New England are of two fairly distinct types. The more common one accompanies an area of high pressure that has its inception in the British Northwest or its vicinity, progresses regularly eastward over the northern border States and the southern sections of Canada to the north Atlantic coast. When the HIGH is pronounced and of considerable intensity, the cold wave can be anticipated, at times, several days in advance of its arrival in New England. As a rule, the cold wave is of greater intensity when the HIGH is preceded by a LOW that moves southeasterly over New England, or by diminishing pressure along the southern coast of New England. This type of cold wave is well illustrated in the series of weather maps from January 12 to 14, inclusive, 1914. (See figs. 84–85.)

The second type is of less frequent occurrence, but at times the cold is of great intensity. It sometimes comes with little premonition, can be forecast but a short time in advance of its arrival, and occasionally it arrives before warnings can be issued. These cold waves accompany HIGHS that, apparently, rapidly move southeastward from the Hudson Bay region, or that develop quickly in southeastern Canada in connection with diminishing pressure in the Ohio Valley and thence eastward. The HIGH moves eastward over New England with attending low temperatures. This type of cold wave is well shown in weather maps of February 9 to 14, 1914. The low temperature in Boston during this cold wave equaled the record of February since the establishing of the station in 1870. Sometimes the first intimation of cold waves of this class is a moderate to strong northerly wind at White River, or Cochrane, Ontario, that can not be accounted for by the pressure gradient to the southward of these stations, the wind force being due to the HIGH to the northward, outside of the field of observation. Failure to announce cold waves in the forecasts and warnings, if any, generally occurs with conditions under which the latter class is produced.

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COLD WAVES IN WEST GULF DISTRICT.

By I. M. Cline, District Forecaster.

The direction of movement of the LOWS which precede the HIGHS and cold waves in the different months is a factor which must be carefully studied by the forecaster because many of the LOWS which precede the occurrence of cold waves in the west Gulf district move southward into central Texas, then recurve sharply to the northeast, their centers passing over or east of southern Arkansas, or still farther eastward. Very few cold waves occur at Little Rock, and Fort Smith, Ark., as compared with the number of cold waves which occur at Bentonville, Ark., Oklahoma, Okla., and Abilene, and Palestine, Tex., and Shreveport, La. The number of cold waves that occur at Bentonville, Ark., and Oklahoma, Okla., is three times greater than the number that occur at Fort Smith and four times greater than the number that occur at Little Rock, Ark.

During the recurve of LOWS in Texas, Arkansas is immediately in front of, or in the eastern segment of the LOW; after the recurve and during the movement of the LOW toward the northeast Arkansas is in the segment to the northwestward of the path of progression of the center. This movement gives a slow fall in temperature over the State, except the extreme northwestern portion, frequently extending over 48 hours so that the required fall in temperature does not occur within the prescribed time even though the verifying temperature is reached. The exceptions to this rule are few and occur when the cold wave is exceptionally intense or the recurve and movement of the LOW toward the northeast is very rapid. Cold waves occur at Little Rock and Fort Smith most frequently when the center of the LOW preceding the cold wave moves eastward through or immediately to the north of Oklahoma and Arkansas. The number of cold waves which occurs at Little Rock and Fort Smith is about equal in the colder months except February, when the number that occurs at Fort Smith is nearly double the number that occurs at Little Rock. This is probably due to the fact that LOWS in February which are followed by cold waves in this district move farther south into Texas before recurving to the northeast and the paths of the centers of such LOWS are farther to the south than in other months.

If the LOW does not recurve before it reaches the Gulf coast the cold wave will usually extend to the coast line. The location of the center of the LOW at the time of recurving and the direction of movement after recurving determines the stations in this district at which cold waves will occur.

Cold waves move southward over the north-central portion of this district with great rapidity. Cold waves frequently occur at Abilene, Tex., within 12 hours after they reach Bentonville and Oklahoma.

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They reach Little Rock, Ark.; Shreveport, La., and Galveston, Tex., 18 to 24 hours after they reach Oklahoma, and they reach New Orleans about 12 to 24 hours later than they occur at Galveston and Shreveport.

Cold waves occur at El Paso, Tex., about once a year on an average. Cold-wave warnings for that station should be issued with caution, unless the crest of the HIGH is well to the northwestward, over the Rocky Mountain-Plateau region.

COLD WAVES IN DENVER FORECAST DISTRICT.

By F. H. BRANDENBURG, District Forcaster.

In the Denver forecast district, as in other parts of the United States, cold waves occur principally in December, January, and February, occasionally in November and March, and rarely in October and April, and then only in Utah and Colorado.

It will, of course, be understood that the HIGHS are of considerable magnitude and intensity and attended by abnormally low temperatures; that the LOWS are deep depressions and attended by normal temperatures or temperatures above the normal.

A cold wave may be expected in eastern Colorado when there is a LOW or one forming on the middle eastern or southeastern Rocky Mountain slope, and anticyclonic conditions are advancing from the northwest or north (Jan. 9, p. m., 1909); when there is a LOW in New Mexico, southwestern Colorado, or northern Arizona, and the front of the LOW has crossed the Continental Divide, and anticyclonic conditions with abnormally low temperatures prevail on the northeastern Rocky Mountain slope.

In western Colorado cold waves are relatively infrequent. A cold wave is to be expected when there is a LOW in the vicinity moving east or southeastward, and a HIGH is advancing from the northwest, west, or southwest (Jan. 5–6, 1915); also when a trough of low pressure extending from southwest to northeast, with steep gradients to the westward, crosses the State.

A cold wave will usually overspread the entire State of Colorado when the axis of the LOW is east and west, extending to both sides of the Continental Divide in Colorado or New Mexico, and the axis of the HIGH in the north is also east and west or nearly so; also when there is reason to expect the axis of a LOW in the middle Rocky Mountain region will change its direction in a few hours to an east and west direction at a time when anticyclonic conditions prevail to the northward (Jan. 24–25, 1902).

In Utah a cold wave may be expected following the movement of the center of a LOW northeast, east, or southeastward across the State.

In Arizona a cold wave may be expected when the center of a LOW moves northeast, east, or southeastward across the State.

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A cold wave may be expected in eastern New Mexico when the center or the front of a LOW has reached the eastern Rocky Mountain slope in New Mexico or Mexico, and high pressure overlies the region northward.

A cold wave will overspread the entire State of New Mexico when the center of a LOW moves eastward across the State, and also when a LOW moves eastward through northern Mexico, and high pressure is moving from the west or northwest.

COLD WAVES IN NORTH PACIFIC DISTRICT.

By EDWARD A. BEALS, District Forecaster.

During the late fall, winter, and early spring months any building up of pressure over British Columbia, Alberta, or western Montana, combined with a deepening of a LOW near the Oregon coast, requires careful attention from the forecaster, as it is the first intimation of a cold wave that possibly may sweep the North Pacific States. The extent of the area affected will depend upon the movement of the LOW.

Frequently a mass of air over eastern British Columbia and Alberta, attended by very low temperatures, will be on the verge of draining into northern Idaho and eastern Washington, but air movement in this direction will be checked by a LOW over the Columbia River Valley. It then seems as if a battle of nature's forces took place, with no indication as to which force would dominate. Often this condition will prevail for 24 to 48 hours, and sometimes longer, with no advantage to either side. During such periods the weather forecaster has many anxious moments, as he must be extremely careful, or he will issue an unnecessary cold-wave warning.

The longer the two forces remain opposed to each other without either gaining the advantage the greater the prospect that the LOW will maintain its supremacy, and the cold air attending the high-pressure area will drift southeastward along the eastern slope of the Rocky Mountains, and none will drain into the North Pacific States.

When the foregoing conditions prevail the best index the forecaster has is the wind direction and velocity at the stations within the cold area and especially at those stations nearest to the northern boundary of Washington and the northern and eastern boundary of Idaho, i. e., Kamloops, Calgary, Kalispell, Havre, and Helena. Should the air be quiet at those stations the conditions are favorable for no cold wave in this district, but should the wind be from the north or northeast and the movement greater than 8 or 10 miles an hour it is almost certain that a cold wave will occur. The only thing to be done is to call for frequent special observations and issue a warning for the northern sections as soon as assured that the air

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movement has set in toward the district. Owing to the difficulty of determining this question eastern Washington and northern Idaho ordinarily will not receive information so far in advance as will the southern portion of the district.

After being assured that a cold wave will spread over the northern section, it is necessary to be extremely cautious in extending the warning to southern Idaho. This section is surrounded by mountains. Lows sometimes move from the Oregon coast to this locality and there remain stationary for several days. When this movement takes place southern Idaho may escape a cold wave, or if one occurs it will not be as severe as was expected.

Cold waves in the Eastern States occur following the advance of a LOW attended by warm southerly winds, which warm area is later occupied by a HIGH from the front of which blow cold north or northwest winds. Usually the HIGH is to the northwest of the LOW, the movement of the former being toward the southeast or east and of the latter either to the east, northeast, or southeast.

Cold waves in the North Pacific States take place under similar conditions, so far as the movement of the HIGH into the field formerly occupied by the LOW is concerned, but there is this difference: In the North Pacific Coast States the LOW must have a movement toward the south or southeast, and the HIGH, instead of being to the northwest of the LOW, is either north or northeast of it. With the HIGH in the north or northeast and the LOW moving so as to permit cold air to flow into Washington and Idaho, it is believed the danger of a cold wave in the Northern States east of the Rocky Mountains from the same HIGH is lessened, for the reason that the cold air within the HIGH is partly diverted into Washington and Idaho, and only that part left can flow into the States east of the Rocky Mountains, and this part can not cover as great an area as would have been the case if all the cold air found an outlet along the east slope of the Rocky Mountains.

So far cold waves have been discussed on the theory that they are caused by a transference of cold air from one part of the country to another, but as a matter of fact cold air is often due entirely to nocturnal radiation; and sometimes in the North Pacific States a cold wave will occur locally from this cause. To predict this class of cold waves, the conditions governing the prediction of frost apply, and they can be followed by merely extending the limiting degree to a lower point on the scale of the thermometer. As stated in my paper on weather forecasting in the North Pacific district: "When cold air drains into the valleys in Oregon, Washington, and Idaho, the cold weather will last for several days," and a return to warmer weather should not be predicted until the district comes under the influence of a low of sufficient energy to cause strong southerly winds.

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The type shown on the a. m. weather maps of February 9, 10, and 11, 1905, is nearly a perfect type of a cold wave in this district. The conditions shown on the p. m. weather map of February 4 and the a. m. of February 5, 1914, also are good types.

COLD WAVES IN SOUTH PACIFIC DISTRICT.

By G. H. WILLSON, District Forecaster.

In forecasting cold waves and frost in this district it is necessary to first have a clear knowledge of the topography of the country and then make the forecasts conform to the natural divisions. Both temperature and precipitation are quite different east and west of the Sierra Nevada and north and south of the Siskiyou Mountains. This is plainly shown by the flora on the several sides of the above-mentioned mountain ranges. Therefore, any discussion of weather forecasting for this district must be by natural divisions.

In the extreme northeast portion of California a part of the State lies east of the main range of the Sierra Nevada Mountains, with weather conditions similar to those in Nevada, where the temperature in winter often falls to zero or below and the changes are rapid and great. In the valleys and foothills of the remaining portion of the State, except along the immediate coast, the weather is subtropic in character. On the western slope of the Sierra the conditions vary from the citrus-fruit belt of the foothills to the perpetual snow fields near the summit of the range.

In the Sacramento and San Joaquin Valleys and foothill regions during the passage of a cold wave over the Plateau the air flows over the Sierra Nevada and Siskiyou Mountains into the valleys below, and is warmed dynamically in passing down the mountain slopes; consequently, unless the conditions are well marked, the temperature in these sections will not fall much, if any, below freezing. In the fruit region of southern California, the Sierra Madre and San Bernardino Mountains form a similar shield for that section.

Cold waves occur in this district when HIGHS with very low temperature extending well to the west of the main range of the Rocky Mountains, move southward over the Canadian Northwest, and there is a LOW lying to the south or southwest over the Pacific coast or Plateau region. If the HIGH is over Alberta and is accompanied by temperatures below zero at Calgary, but not unusually low at Barkerville and Kamloops, the cold wave may extend into Nevada, provided the barometric gradient to the southwest is sufficient to allow the cold air to flow in that direction. If the LOW lies to the east or southeast of the HIGH the latter will generally move southeastward, giving a sharp fall in temperature over Nevada, but

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very seldom a cold wave, and temperature changes in California will not be marked.

If a LOW overlies the Pacific coast when the HIGH appears over British Columbia or Alberta, the situation is more complicated and the resulting weather is influenced by the conditions prevailing over the Rocky Mountain region and Plains States. A LOW in those sections will in most cases cause a movement of the HIGH and accompanying cold weather to the east or southeast, and give rain at the lower levels and snow in the mountains of this district, with a slight rise in temperature. If, on the other hand, the pressure is comparatively high over the Rocky Mountain region and Plains States, the northern HIGH will continue to move southward, causing sharp falls in temperature; and the development of a cold wave will depend upon the rapidity of the southerly movement of the HIGH, the position and energy of the LOW, and the condition of the skies. A rapid movement of the HIGH with clear skies will generally give a cold wave with high north to northeast winds and always a sharp fall in temperature. If the sky is covered with heavy clouds the temperature fall will not be great, and instead of a cold wave there will generally be a cold, drizzling rain with snow flurries in the mountains.

HIGHS moving in from the ocean are seldom accompanied by cold waves west of the Sierra Nevada Mountains, unless reinforced by another HIGH moving south over British Columbia or Alberta with sufficient gradient to the south or southeast to bring in the cold air from the northeast (Jan. 19–21, 1913). Occasionally HIGHS when well marked and showing low temperatures as they approach the coast will cause a moderate cold wave over Nevada. One reason technical cold waves (temperature falls of 16° to a minimum of 32°) seldom occur in California is that while the temperature may fall 16° or more, it seldom reaches 32° until the second or third day after the fall begins and then only by slow stages.

It will be seen from the foregoing that the development of a cold wave in California is closely associated with and dependent upon conditions which give steep barometric gradients from the north and northeast, and are therefore accompanied by high north and northeast winds.

While the above outlines in a general way the conditions preceding a cold wave in this district, it alone will not be of much value except as a broad basis for forecasting them. The writer relies almost entirely upon the pressure change chart, and especially the 12-hour changes, to indicate the conditions to be expected. Rapid pressure changes usually give corresponding changes in temperature and indicate the direction and extent of them. They point out the source from which the air is being drawn and, therefore, are an index of the temperature falls to be expected.

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Following are some dates of cold-wave types for this district:

December 31, 1906.—Ideal map for cold wave in Nevada and Inyo County, Cal. (Independence).

January 12, 1907.—Favorable for cold wave, but did not verify. Temperature fell 20° at Reno and 18° at Winnemucca, but did not reach a minimum of 10°.

January 15, 1907.—Favorable for cold wave, but failed except at Independence. Temperature fell to zero at both Reno and Winnemucca, but the fall was only 14° and 16°, respectively.

December 5, 1909.—Favorable for cold wave and was verified at Reno and Independence, but failed at Winnemucca and Tonopah.

January 1, 1910.—Favorable for cold wave and was verified at Winnemucca and Independence, but failed at Reno and Tonopah.

January 16, 1910.—Very unfavorable, but cold wave occurred at Winnemucca which appeared to be local.

January 15, 1911.—Favorable for cold wave and verified at Winnemucca.

December 28, 1911.—Favorable for cold wave and verified at Winnemucca and Independence.

December 26, 1913.—Not favorable, but cold wave occurred at Winnemucca which appeared to be local.

December 20, 1914.—Not favorable, but local cold wave occurred at Winnemucca.

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CHAPTER VII.

FROST WARNINGS.

By HENRY J. COX, Professor of Meteorology.

[With contributions by District Forecasters John W. Smith, Boston, Mass.; Isaac M. Cline, New Orleans, La.; Frederick H. Brandenburg, Denver, Colo.; Edward A. Beals, Portland, Oreg.; and George H. Willson, San Francisco, Cal.]

Frost, formation of 177
Damage by 178
Relation between temperatures of air and vegetation 179
Charts of frost dates in the United States 180
Frost, effect of topography upon 181
Bearing of soil moisture upon 187
Effect of sanding, draining, and cultivation 187
In Pacific Coast districts 188
In Rocky Mountain region 194
Frost forecasting:
The median temperature as a factor in 201
The relative humidity 203
In cranberry marshes in Wisconsin 204
In cranberry marshes in Massachusetts 207
In the New Orleans district 208
In the Denver district 209
In the Portland, Oreg., district 211
In the San Francisco district 214

FORMATION OF FROST.

What is generally known in this country as frost is the moisture of the air condensed at freezing temperature on plants or other objects near the surface of the earth, and it is often referred to as white frost or hoar frost, because of its color. It is to this phenomenon that the word "frost" applies in the work of the Weather Bureau. The term in many of the European countries, however, has reference to freezing temperature only, and in England "frost" and "the freezing point" are considered synonymous, such an expression as "4° of frost" meaning "4° below the freezing point." The term "black frost," sometimes used in this country, has reference to temperatures sufficiently low to form ice and more nearly coincides with the meaning of the word "frost" in England.

The subject of frost naturally follows the discussion of cold waves, as frost usually occurs within areas of high pressure such as bring cold waves. Frost, however, is of interest to forecasters during the crop season only, and its occurrence during winter in the United

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States is not of moment except in California and Florida, and other portions of the Gulf region, where plant growth is maintained during the entire year. It is in the spring and fall that possible damage from frost is important over the greater portion of this country, while in the States along the northern frontier east of the Rockies, in the elevated sections of the country, and in bog lands, where vegetation is dense and the air drainage poor, frost occurs even in the summer months.

Just as dew is condensed upon the surfaces of plants or other objects at a temperature above freezing, so frost is condensed at freezing temperature; although it may form upon these surfaces when the temperature of the air is considerably above the freezing point. The temperature of the surface of the object, however, must of course be as low as freezing. Plants on clear, cool nights, when radiation is active, lose heat much more rapidly than does the air, with a resulting lowering of the temperature. Both green vegetation and a dark soil are excellent radiators; each, according to Humphreys, radiating about two-thirds as much as does an ideal black body at the same temperature. (October Monthly Weather Review, 1914, p. 564.)

Frost is more likely to form when there is at least a moderate amount of moisture present in the air, so that with a falling temperature the dew point is reached on the surfaces of objects. In a dry atmosphere the temperature of an object may fall below the freezing point without any evidence of frost formation, and such a condition may be just as damaging as if frost were present, or even more so; but usually this is not the case, because in dry sections the temperature remains at the lowest point for only a brief period, the range in daily temperature in these sections being relatively great; and no sooner does the temperature reach the minimum than it begins to rise again, while in sections where the air is not dry the temperature may remain at the lowest point for a considerable period. Moreover, in dry regions, plants are subjected to low temperatures frequently and become hardy and have a correspondingly greater resisting power.

Dry freezes, without any frost formation, sometimes occur in various sections, simply as a result of low temperature and strong winds, and these are far more destructive than ordinary frost.

Damage by frost.—Frost itself does not do any damage, but it is rather a protection to the objects upon which it forms. Moreover, in its formation, it gives off to the air a certain amount of latent heat which tends to prevent the temperature from falling lower. Frost is merely evidence of freezing temperature at the surfaces upon which it forms, and this temperature is injurious to plant tissue in a greater or less degree, depending upon its physiological condition,

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upon how low a temperature is reached and how long the critical temperature continues, congealing the water in the intercellular spaces of the tissue into ice and thus preventing a further circulation of moisture in the plant. The word "frost," then, for obvious reasons, is used by forecasters to designate temperatures damaging to vegetation, and the forecast is usually qualified by the employment of the words "light," "heavy," and "killing"; and when conditions appear to be serious, a prediction of freezing temperature is sometimes made, such a warning being strongest because it presages a condition that is serious. During the crop-growing season frost practically never occurs except in clear or at least partly clear weather and when the wind is light, while freezing temperature may occur in windy and cloudy weather. However, the distribution of temperature and pressure conditions is sometimes such that a forecast of frost may be made for one State and freezing temperature for one adjoining it; similarly, forecasts of killing, and light or heavy frost, for adjoining sections in the same district.

The terms, "killing frost" and "freezing temperature," so far as damage to vegetation is concerned, are more or less interchangeable. Killing frost often occurs without the temperature of the air falling to the freezing point, but in the arid and subarid sections of the country it seldom occurs until the temperature of the air has fallen below the freezing point. Moreover, light frost often occurs when the temperature of the air is as high as 40° F., and even higher.

RELATION BETWEEN THE TEMPERATURE OF THE AIR AND THAT OF VEGETATION.

As stated before, the surface temperature of a plant will often differ considerably from the temperature of the air. During a research made in the cranberry marshes of Wisconsin in 1906–1910 by the writer (Weather Bureau Bulletin T, Frost and Temperature Conditions in the Cranberry Marshes of Wisconsin) it was found that minimum thermometers exposed in the open, 5 inches above the ground and touching the tops of the vines, averaged for an entire season, 2.8° below those at the same elevation above the ground in shelters nearby. The greatest differences were noted in a section where the vegetation was heaviest, the minimum in the open there averaging 3.7° lower than the air temperature in the shelter. On clear, cool nights, with little or no wind, the differences were large, the greatest being 9.9°, but there was little difference between any of the thermometers on cloudy and windy nights.

Effect of environment on the occurrence of frost.—We have seen that the temperature of the plant tissue depends upon its environment; that is, the character and moisture of the soil and the sur-

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rounding vegetation. It also depends upon the height of the tissue above the surface of the ground. The lowest night temperatures occur a few inches above the ground, it being warmer on the immediate surface because of the heat conducted from the soil. At an elevation of 3 feet the minimum temperatures are usually considerably higher than at a few inches above the ground; but at this elevation and above the night temperature is not affected by the character of the soil or the surface vegetation, which reaches a few inches above the ground only, as shown in Weather Bureau Bulletin T. Undoubtedly, however, vegetation higher up, such as the foliage of trees, affects the temperature of contiguous air at higher elevations.

Value of frost warning.—Frost warnings are of much greater importance during the blooming period and while the fruit is green than later in the season when it is approaching maturity. The liability to damage is much greater in the spring when the bloom is unusually early because of a prolonged warm period, as in the seasons of 1907 and 1910, which will be referred to later. Such spring frosts are often very damaging in the northern and central portions of the country. The early frost in the fall ordinarily does not damage the fruit, but if the period of low temperature is prolonged, the fruit does not fully mature. In the cranberry marshes a severe frost, which occurs in midsummer with temperatures sufficiently low to damage the growing berry and also the terminal bud upon which the crop of the ensuing year depends, is by far the most serious. The frost of August 8, 1904, in the Wisconsin bogs was attended by temperatures in the open as low as 25°, and not only caused great damage to the crop of 1904, but affected that of 1905 as well. (See weather maps of Aug. 7–8, 1904, reproduced as figs. 101 and 102. Facing p. 186.)

CHARTS OF FROST DATES IN THE UNITED STATES.

There is, as stated before, a wide range in the seasons of the year when frost is damaging to vegetation and produce in various portions of the country. There are some places in the extreme North and in the elevated sections of the country where frost is possible every month of the year; in the extreme South it is usually confined to the winter season, while in intermediate sections it is of importance only in the spring and fall. In connection with these matters the four charts used by Mr. P. C. Day, climatologist, in Weather Bureau Bulletin V, Frost Data of the United States, have been reproduced, as follows: Figure 97 shows the average date of the last killing frost in the spring; figure 98, the latest date on which a killing frost has occurred in spring; figure 99, the average date of the first killing frost in autumn; and figure 100, the earliest date on which a killing frost has occurred in autumn.

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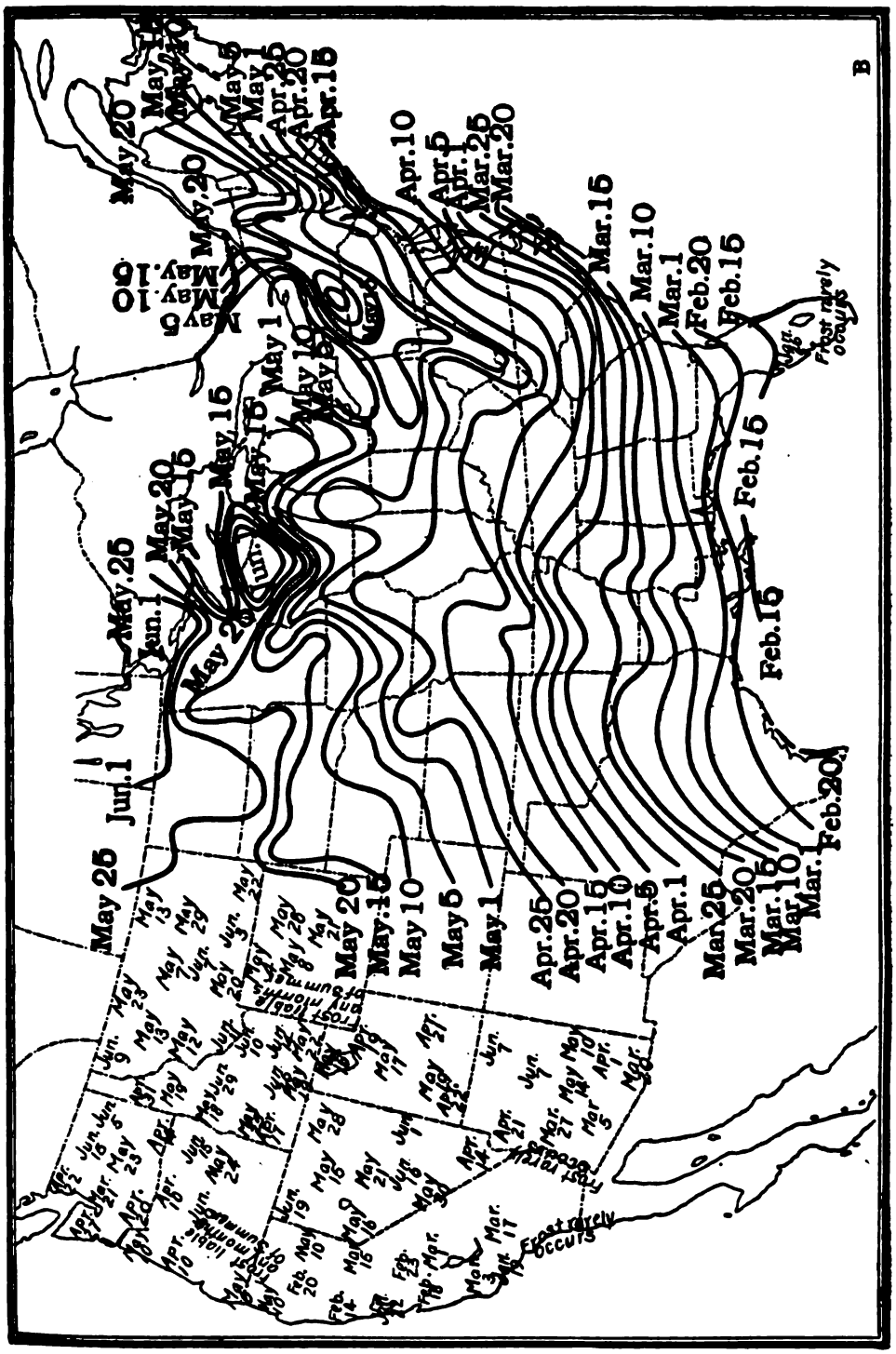

FIG. 97.—The average date of the last killing frost in spring.

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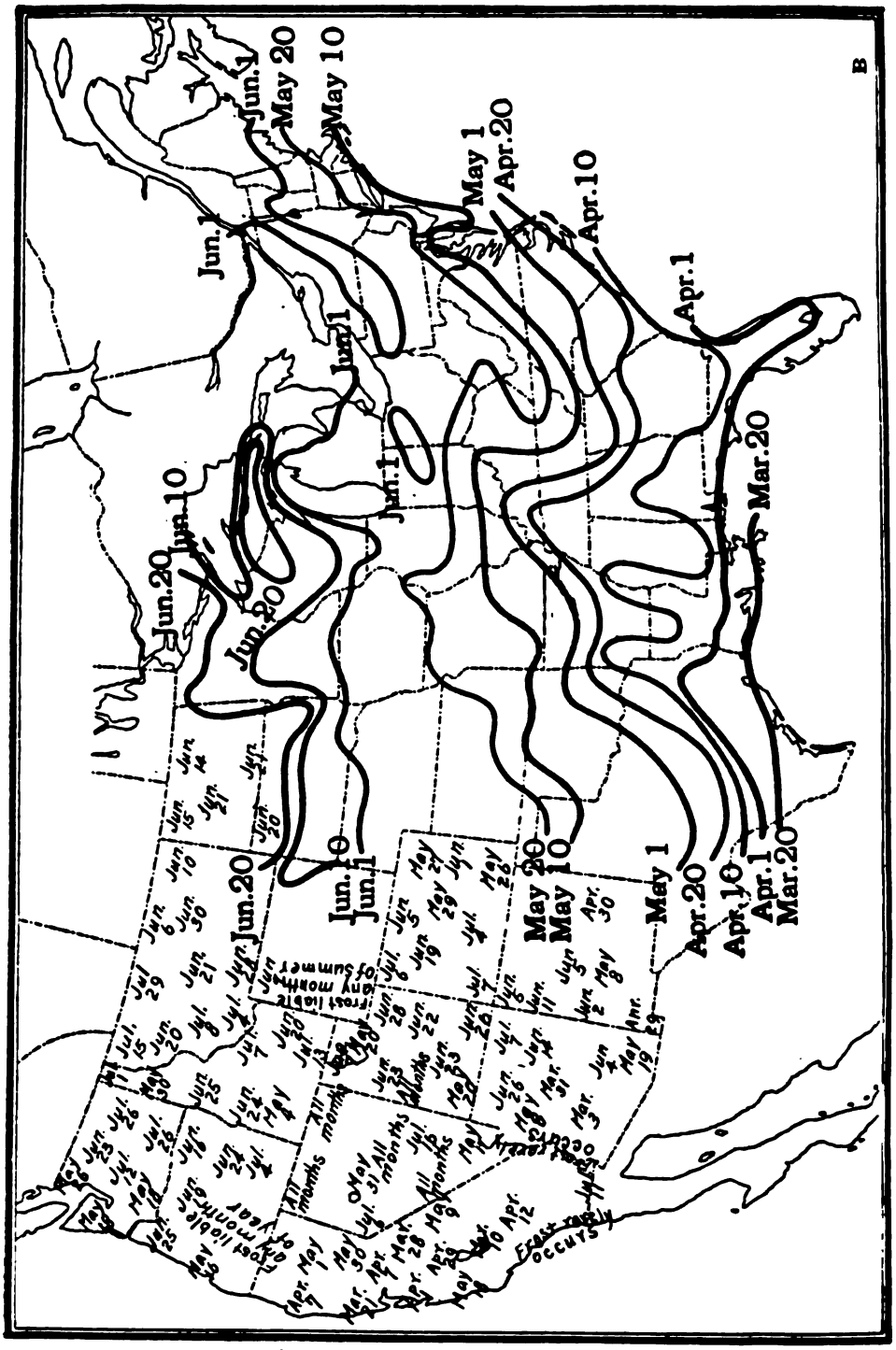

FIG. 98.—The latest date on which killing frost has occurred in spring.

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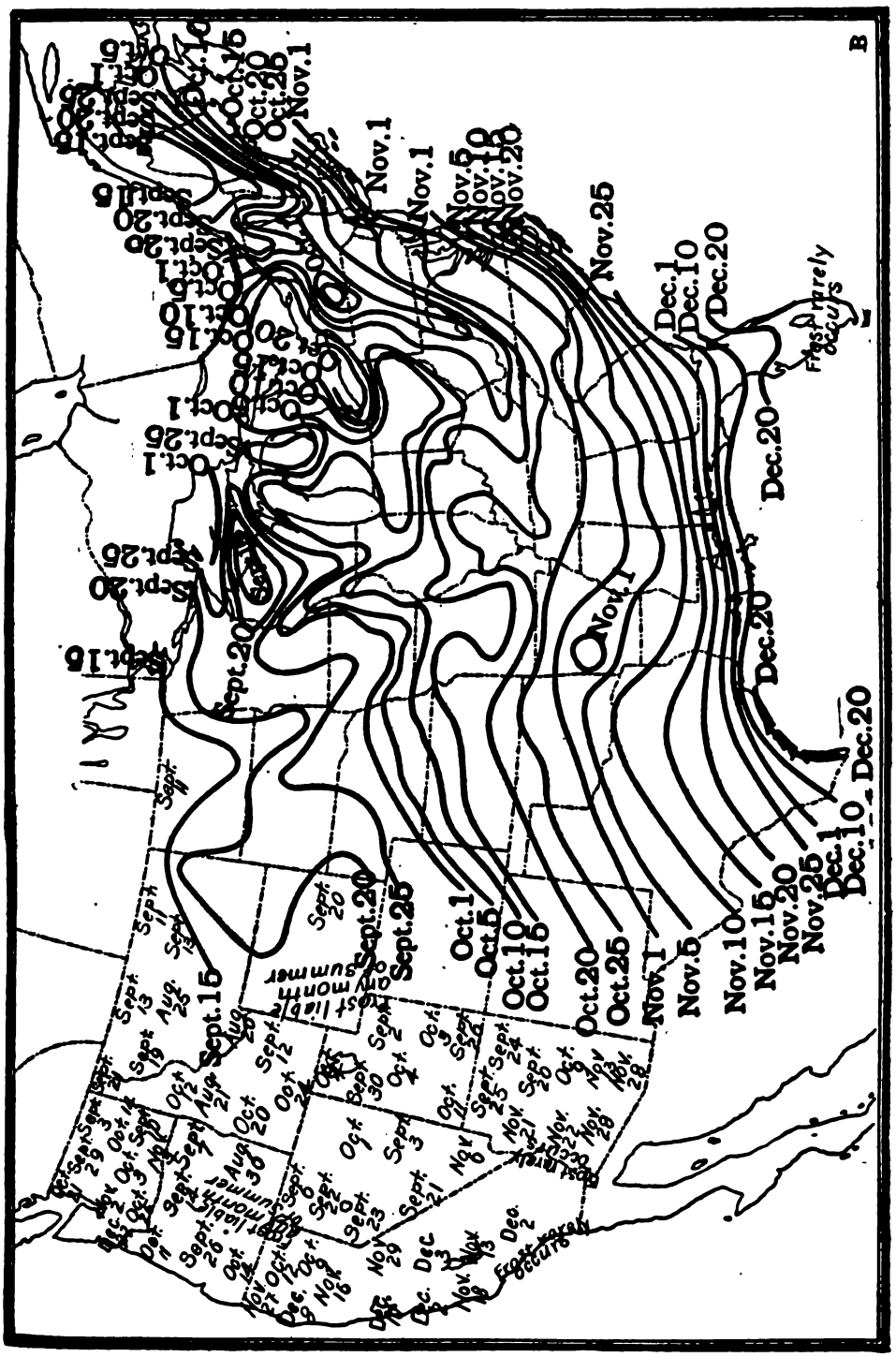

FIG. 99.—The average date of the first killing frost in autumn.

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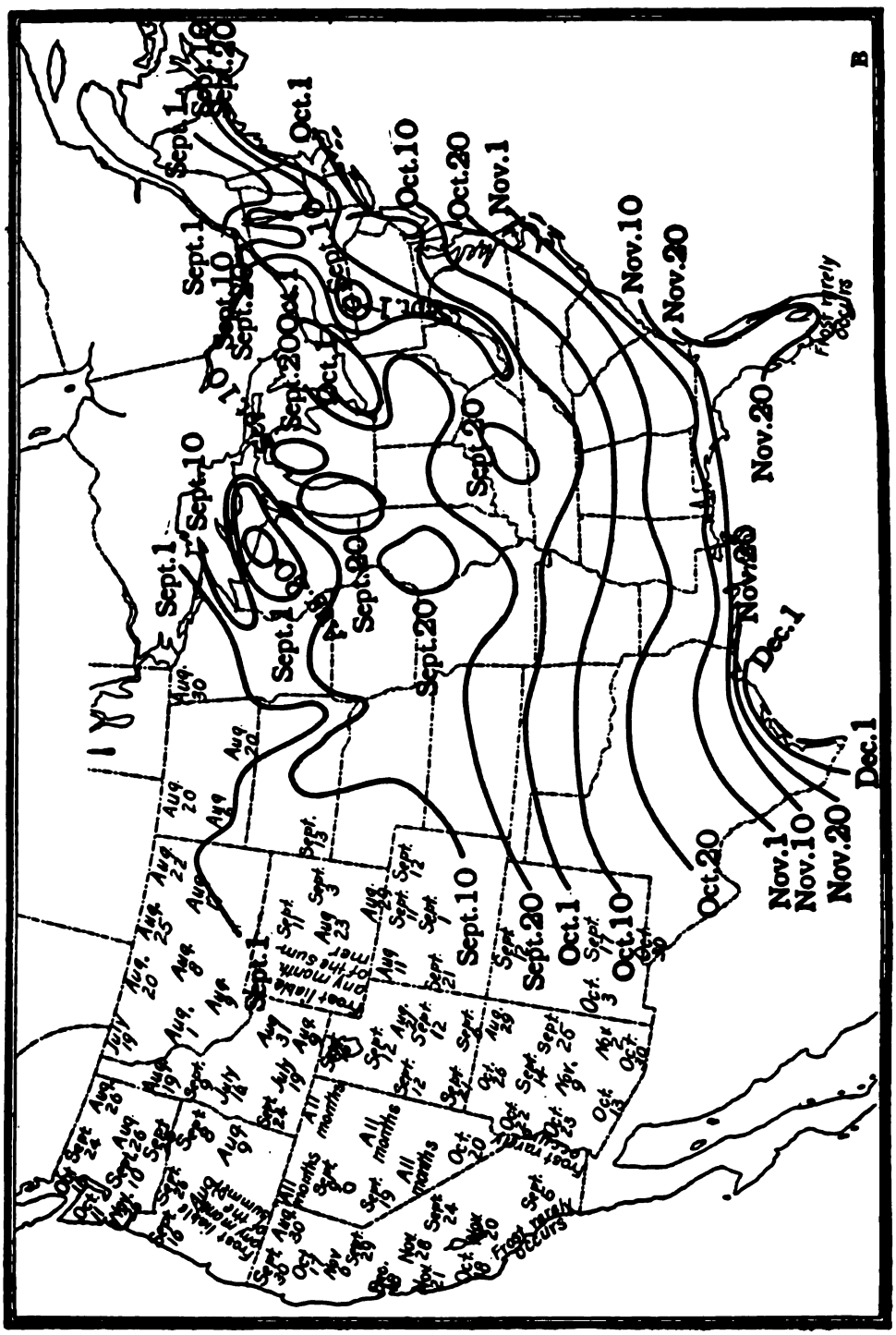

FIG. 100.—The earliest date on which killing frost has occurred in autumn.

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EFFECT OF TOPOGRAPHY.

Frost often occurs on still, clear nights on a valley floor, while points higher up on the slopes escape, the temperature sometimes differing as much as 10° to 15° and even 20° over limited areas. On a windy night the temperature does not differ materially at neighboring points in a hilly country, as the warmer air from above is being continually mixed with cooler air near the surface. Hence, when the topography of the country in such sections permits the free circulation of the air, frost is less likely. In some valleys, because of the configuration of the country, there is usually more or less wind and a consequent mixing of air on cool, clear nights, while other valleys are so situated that there is very little movement of air, and it is on the slopes surrounding the latter that thermal belts are most pronounced.

The probability of frost is then diminished where the air drainage is good. Frost is most likely in pockets where the air is confined and prevented from flowing lower down. These are commonly called frost pockets. Where the configuration of the country is such that there is a movement of air draining down to lower levels in a valley, frost is less likely in the upper portions of the valley. So it is less frequent in a canyon, where the wind movement is free, than in a valley. A good example of this condition is found at Palisades and Grand Junction in the valley of the Grand River in western Colorado. The spring season at Palisades in the canyon is generally a week or two in advance of that at Grand Junction, a few miles lower down, and frost is less likely in the canyon than in the lower reaches of the valley.

The question of topography is most important. Frost may usually be expected on low ground at times when higher ground escapes visitation, and the lesson taught is that early and tender crops should, as far as practicable, be confined to hillsides and mountain slopes, and later and hardier crops to the lowlands and valleys.

Effect of large bodies of water on temperature.—The proximity of large bodies of water is also of importance in connection with the occurrence of frost. In the autumn the temperature of the water is far above the temperature of the air in a cold HIGH not affected by water influence.

For a 10-year period, from 1902 to 1911, inclusive, it was found that the mean daily temperature of the air at Chicago in the autumn averaged higher than the temperature of the water of Lake Michigan[1] until about September 25 (Weather and Climate of Chicago, p. 43, Cox and Armington), after which date the temperature of the water averaged higher. As the daily range in water temperature

[1] Observations of water temperature made 24 feet below the surface.

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for all seasons is almost inappreciable, its mean and minimum temperatures are nearly the same, but the daily range in air temperature for autumn at Chicago is 14°, and its minimum temperature would therefore be about 7° below the mean, thus showing a still greater contrast between the temperature of the water and the minimum temperature of the air in that season.

It should be evident that in the season of the year when the temperature of the water is higher than that of the air the water influence is the most pronounced in warding off frost in contiguous sections, especially when the wind blows from the water. In the spring the influence of the water in warding off frost is not so great, because the temperature of the water then is lower than that of the air. At Chicago the average air temperature in the wintertime remains below that of the water only until February 20, after which through the spring and summer it continues warmer than the lake water. These data of air and water temperature, strictly speaking, have application to Chicago and the southern end of Lake Michigan only, but it is probable that a similar relation exists between the air and water temperatures at other lake or coast cities.

It can be seen by referring to figures 97–99 that the area affected by frost in the Florida Peninsula usually reaches much farther south in the interior than along the coasts. This is because of the water influence on the temperature of the air. Its effect, especially in the autumn, is most pronounced on the eastern and southern coasts of the country and in the Great Lakes region, as shown by the paralleling of the lines with the shores, illustrated by the same figures as before. This happens even along the Atlantic coast where the prevailing winds are from the west and not from the water. As a general proposition, however, it may be stated that the effect of water in warding off frosts in the spring, especially in northern sections, because of the lower temperature of the water, is not so pronounced as in the autumn, but it is nevertheless quite noticeable. In this connection a study of its effect in the Great Lakes region is interesting. By referring to figure 97 it will be seen that the average date of last killing frost in the spring in that district is later and later as the distance from the Lakes increases. Aside from the fact that killing frosts occur earlier in autumn in the interior than near the Lakes, the influence of the prevailing westerlies in that season is such as to postpone still further the coming of frost in sections contiguous to the eastern shores of the Lakes, as shown by figure 99. The effect of the westerlies is felt to a degree far into the interior, and this is demonstrated by a comparison of conditions in the Lower Michigan Peninsula and those in Wisconsin on the other side of Lake Michigan. Perhaps the water influence in the autumn is best illustrated in figure 99 by the line of October 5—the

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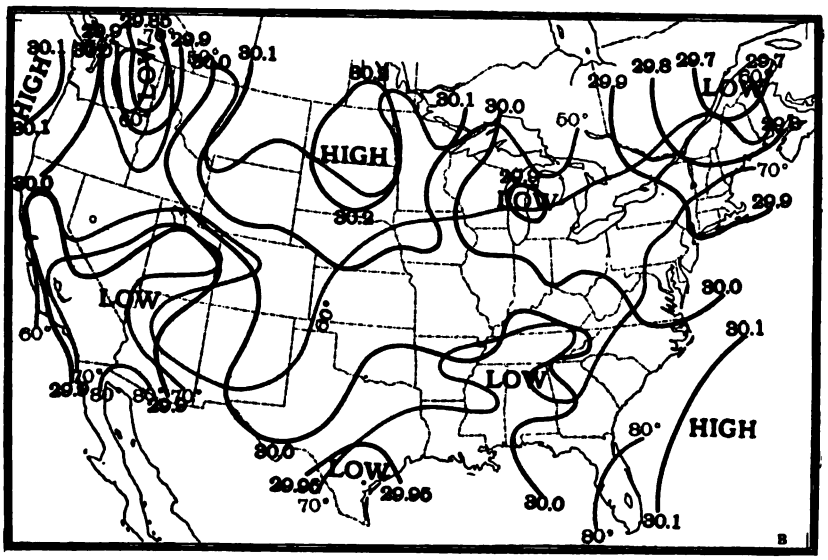

Fig. 101.—August 7, 1904, summer frost in Wisconsin.

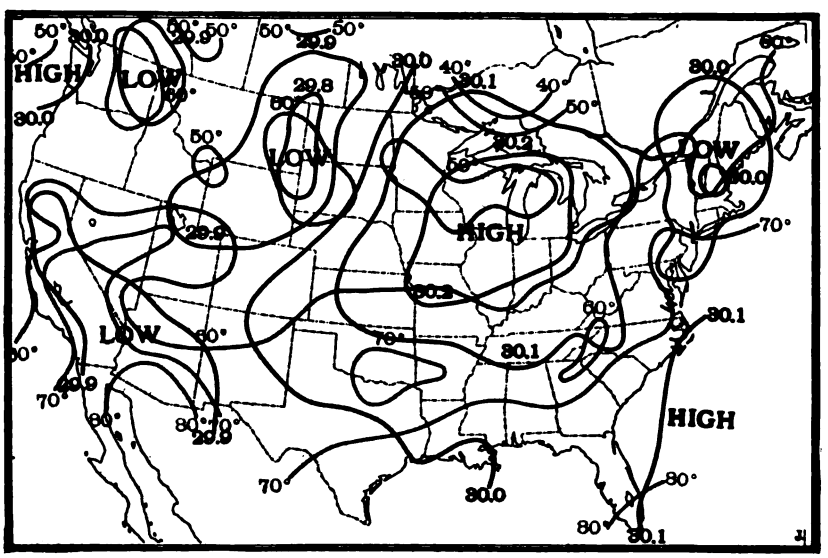

Fig. 102.—August 8, 1904, summer frost in Wisconsin.

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average date of the first killing frost in autumn—which passes from the northeastern coast of the Lower Michigan Peninsula irregularly southward to the middle Ohio Valley.

Bearing upon the problem of damp and moist soils, respectively.—While a damp soil favors the occurrence of frost, a very wet soil has the opposite effect.

A distinction must be made, then, between damp soil and thoroughly saturated soil. When frost was observed in many places in Oregon on the mornings of April 13, 14, and 15, 1912, it did not occur in the Rogue River Valley because of the previous heavy rains and wet snows which turned the soil in the orchards into a veritable sludge. The temperature of the air was close to the freezing point, but frost might as well have been expected on the surface of a lake as in the orchards under such conditions. The writer was making a visit to the fruit orchards in Oregon at this time and was much interested in the phenomenon.

The soil was so wet from continued rains in the middle Missouri and upper Mississippi Valleys on October 10–11, 1914 (see weather maps of those dates), that no frost occurred, although, aside from the wet soil, all the conditions seemed favorable for its formation. The explanation is found chiefly in the high specific heat of water. A certain quantity of heat lost during the nighttime from relatively dry ground and its vegetable cover cools the exposed portions of these poor heat-conducting objects to a very low temperature. An equal loss of heat from the same substances when they are loaded with moisture results in only a small lowering of the temperature, not only because the water must now be cooled in addition to the ground and vegetation, but, as we know, water requires the removal of considerable heat to cool it slightly. The radiation losses from the saturated surfaces may also be less than from the dry surfaces.

Frost does not therefore occur following a heavy rain unless the ground has previously been rather dry, but a light rain on an overcast and windy day is favorable. Then the initial temperature in the evening is low and the soil is cold because of the evaporation of moisture from the surface and the fact that there was no heating of the soil during the day. When the ground is moderately wet and frost occurs it is usually light.

Effect of sanding, draining, and cultivation.—It was found in the study of conditions in the Wisconsin moorlands that frost was less likely in well-drained and weeded areas and in sections where the peat bogs had been sanded. It was shown conclusively that draining, cultivating, and sanding had a decided effect in the prevention of frosts.

The Wisconsin bogs are located in extensive moorlands that reach for many miles, there being no uplands of consequence in the vicinity.

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There are in these marshes more or less timber and brush which serve to break the force of the wind and often at night calms prevail or the winds are very light, so that the warmer air above is not mixed with the colder air near the ground. The temperature conditions in these moorlands vary as much as between the slopes of a mountain and the valley floor, and even in the same bog the night temperatures differ widely. The investigation of the Weather Bureau showed that there was a reason for all these variations; that where the vegetation was densest, the lowest night temperatures occurred because of the rapid radiation; so also where the soil was damp and the drainage poor, because such a soil is warmed less by the sun's rays and in the evaporation of moisture from the surface heat is lost. The character of the soil has much to do with night temperature, the readings being low over a soil such as peat which conducts very poorly and radiates rapidly; and it is chiefly for this reason that the cranberry growers sand their bogs—that is, place a layer of sand 2 or 3 inches in depth over the peat. This serves to conduct the heat received during the day into the soil, and as the heat lost by the sandy soil is partly by conduction to the air above, the temperature of the air over this surface does not fall as low at night as over peat. Sand also prevents rank growth and provides better drainage from the surface. This investigation indicates possibly the causes of the great differences in frost conditions reported in level surfaces in other sections of the country, where no reason for the great variation was clearly apparent. Upon investigation, when such variations occur, it will doubtless be ascertained that there is a difference in the density of the vegetation or in the character and moisture of the soil, or possibly in the proximity to timber.

As stated before, frost occurs during the passage over a district of a cool HIGH. This usually has a pressure of at least two- or three-tenths above the normal, and is often attended by little air movement. These conditions, relatively dry air and absence of cloudiness, are favorable to a large loss of heat by radiation. The consequent cooling during night time in conjunction with the relatively low initial day temperatures, which are likely to be below the normal, naturally lead to temperatures below freezing.

Frost in the Pacific coast districts.—The typical HIGH which causes frost in the North Pacific coast districts during the growing season appears in that section after the passage of a LOW to the east or south with rising barometer. The HIGH first appears in British Columbia or off the North Pacific coast, and later moves in a southeasterly direction. The conditions shown by the weather maps of April 10, 11, 12, and 13, 1911, figures 103, 104, 105, and 106, are typical of spring frost conditions.

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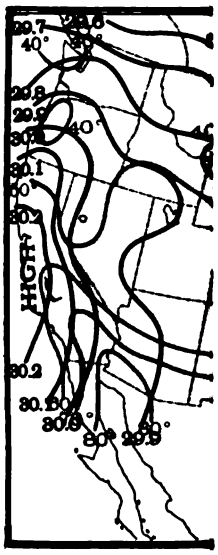

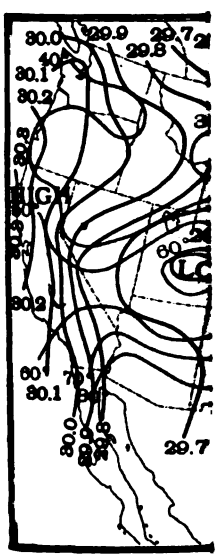

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The pressure in the HIGH by the evening of April 13 had risen to 30.5 inches. A HIGH which overspread the same sections a year later on April 13, 14, and 15, 1912, was not so strong, the pressure being much lower. However, it caused frosts at many points in that section. In the orchards of the Rogue River Valley the night temperatures were close to the freezing point, but because of previous rains and wet snows, the soil there was thoroughly saturated and no frosts occurred, as stated on page 187.

The autumn HIGH in the North Pacific Coast States and its later movement are well represented by the weather maps from September 23–26, 1908. (See figs. 107, 108, 109, and 110.) The ensuing frosts were quite extensive, covering the districts from the coast well into the interior, principally because of a well-developed LOW over the Rocky Mountain region and the southwest which induced a strong flow of cold air across. Frosts were reported repeatedly in the North Pacific district on September 24, 25, and 26, 1908, and even over southern Oregon and the Plateau sections on the 27th.

Such HIGHS as those referred to above do not in the spring and autumn cause frosts in California, or at least in the southern part of that State, and it is only in the winter that they reach to the southern limit of that region. These winter frosts are usually brought by HIGHS or ridges of high pressure extending westward from continental HIGHS that seem to move directly southward. The most notable instance of freezing temperature in southern California occurred on January 7, 1913, when a minimum of 25° was recorded at San Diego, the previous lowest temperature being 32°. Reference should be made to the weather maps of January 5, 6, 7, and 8, 1913. (See figs. 78–81, Chap. VI.) Serious frosts occurred on all four days over the greater portion of southern California, but the lowest temperature was recorded on the 7th, the third day of the freeze. Severe frost in southern California can only occur under similar conditions; that is, after a deep LOW which has previously been centered on the south California coast is displaced by the southerly movement of a HIGH of considerable magnitude. The maps of December 21–23, 1912, also illustrate this type.

Frosts, however, of less importance occur in southern California in the winter, either when a HIGH moves eastward from the Pacific Ocean across the State, as shown by the maps of January 18–20, 1907, or when, as Mr. Ford A. Carpenter says in the October Monthly Weather Review, 1914:

> An immense continental HIGH is apparently too far to the eastward to affect the temperatures, but a slight weakening of the North Pacific LOW allows the influence of the HIGH to be felt by causing a sudden fall in temperature.

as shown by the maps of January 11–12, 1914. Following the frosts which occurred in California from January 18–20, 1907, referred to

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in this paragraph, the HIGH, after passing into the interior from the Pacific, united with another HIGH which had moved down from the British Northwest over the Rocky Mountain and Plateau districts. This latter HIGH was of considerable magnitude and remained stationary over the Plateau for several days, causing a recurrence of frost in California, with the exception of the extreme southwestern portion, on January 21, 22, and 23. On the 20th a LOW appeared on the North Pacific coast, but it weakened during the ensuing 24 hours. This type of continental HIGH causing frosts in California is similar to that referred to by Carpenter.

Frosts in Florida.—In other districts of the country frosts are conditioned by HIGHS of considerable magnitude in their normal movement, ordinarily from the northwest to the southeast. It is usually, however, not before Christmas that frost occurs in southern Florida and seldom before Thanksgiving, and then only in HIGHS of considerable magnitude that have moved down from the northwest across the State of Texas into the Gulf of Mexico, whence they turn and advance eastward in the wake of a LOW over the Atlantic. In fact, in order to cause frosts throughout the Florida Peninsula in any season, either the center of the HIGH must pass across the State, or, if the center passes to the north over Georgia and South Carolina, for instance, the pressure south of the center in Florida must ordinarily be as great as 30.30 inches at Miami and 30.40 inches at Jacksonville with clear weather and northerly winds. A HIGH which moves from the northwest with its center over the Plains States and finally across Florida without passing into the Gulf of Mexico may cause frosts over that State when the pressure is not great, as on November 28, 1903, at which time the barometer was no higher than 30.14 inches at any of the Florida stations. Previously a well marked LOW had been centered in the ocean off the Florida coast. The maps of November 26–28, 1903 (see figs. 111, 112, and 113), illustrate this type; while the maps of January 25–28, 1905, illustrate a type of HIGH which, advancing from the northwest, moves into the Gulf of Mexico before reaching Florida. In this case, the pressure was much greater, the barometer registering 30.54 inches in the northern portion of the peninsula. HIGHS which move into the Gulf are usually of great magnitude when they start in the northwest, sometimes the pressure reaching 31 inches and seldom less than 30.75 inches. But the pressure steadily diminishes in the southeasterly movement. After the HIGH passes over the waters of the Gulf its temperature is, of course, more affected than that of a HIGH which reaches Florida without passing into the Gulf. In spite of this fact, however, the former are usually more severe and more sweeping in character because their initial temperatures are lower and in their southerly course they cover a greater area.

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Another type of HIGH which brings severe cold to Florida but whose center remains north of that State is shown by the maps of February 12–14, 1899 (see figs. 114, 115, and 116), and March 6–8, 1899. In the February cold wave of 1899 the lowest temperatures in over half a century were recorded generally throughout Florida, readings of 10°, 22°, and 28° being reported from Jacksonville, Tampa, and Jupiter, respectively.

However, when a HIGH from the northwest moves in such a direction that its center remains north of the Gulf coast, it usually passes eastward without causing frosts in the Florida peninsula, unless the pressure reaches 30.30 inches as far south as Miami, as stated in a previous paragraph. In fact, more frequently the movement of the area is such that the winds shift to northeasterly and cloudy weather develops over the entire State, as shown by the weather maps of January 21–23, 1912, and March 27–29, 1913.

The frost situation in southern California and the Florida peninsula is most important because growth is maintained there during the entire year. Moreover, in portions of the Gulf States outside of Florida, especially near the coast, the occurrence of frost even in winter is rather serious. We have seen that in the interior of Florida away from the water frost is likely to occur later in the spring and earlier in the autumn than along the western and northern portions of the Gulf coast. When frost overspreads the entire Florida peninsula, it is noted almost invariably in other portions of the Gulf region, as shown by the maps of February 12–14, 1899, and January 25–26, 1905. Such conditions obtain in these sections in connection with the movement of typical cold waves referred to under the discussion of cold waves.

Frost in the Gulf region.—Types of maps which are quite certain to bring frosts to the Gulf States, except along the immediate coast and in the Florida peninsula, are illustrated by those of March 26, 27, and 28, 1913.

The maps of November 27–December 2, 1911, represent an autumn type which was attended by severe frosts at stations on the Gulf coast from Corpus Christi, Tex., eastward to Florida. On the 27th the trough of low pressure reached from the upper Lake region southwestward to Texas, while a HIGH was centered over the far northwest beyond the northern Rockies. The LOW moved northeast and the HIGH southeast, so that freezing temperature or killing frost was noted in the extreme south on November 29–December 2.

Frosts in sections farther north.—These cold HIGHS which are damaging in the Gulf districts, of course, cause relatively low temperatures in the northern and central sections of the country, but they have no effect upon the vegetation there in these seasons unless the temperature is sufficiently low to cause winterkilling. In

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spring, however, these HIGHS often cause destructive frosts in the sections farther north. In spring, HIGHS usually move from the northwest eastward or southeastward to the Great Lakes region, later settling down over the South Atlantic district. Their course at that time of the year is almost directly over the Great Lakes, because of the relatively low temperature of the water,[1] which depresses the isobaric surfaces, permitting an inflow of air aloft and produces, as a consequence, local increase in pressure.

When the early spring has been mild in the northern and central portions of the country with attendant early bloom, frost in April and May is highly destructive to fruit. In 1910 was noted the warmest March within the history of the Weather Bureau over a great portion of the country, and this mild weather continued until about the middle of April. Then ensued a movement of HIGHS from the northwest, one after another, that were attended by damaging frosts to a considerable section of the country east of the Rockies, the frosts extending frequently during the second half of April even into the northern portion of the Gulf region. The Northern States were not free from this visitation until about the close of May, and in the States along the northern frontier frosts did not cease until well into June.

The weather maps during this period are of various types and a study should prove most interesting. The tendency of HIGHS to move from the British Northwest in the direction of the Great Lakes in the spring is most strikingly shown in this series of maps.

From April 18 to 20, while a deep LOW remained over the Lakes, the HIGH, which was centered in eastern Montana, moved southeastward along the Rocky Mountain slope to the western Gulf region. This HIGH was attended by frost as far south as Fort Worth, Tex., and Shreveport, La., and quite generally over the Middle West. The next HIGH, which appeared a few days later, however, divided into two parts in its easterly movement, one center moving to the northern Lake region, while the other pushed southward over the eastern slope of the Rockies. This condition brought abnormally cold weather well into the Southern States, with frosts this time not only at Fort Worth and Shreveport, but also at Vicksburg.

On May 1, when a broad depression covered the southern Rockies and adjoining sections, a cold HIGH appeared in the northern Rocky Mountain region and moved eastward and southeastward, attended by general frost along its track over the Plains States and the Great Lakes region, reaching the latter district on the 3d and remaining there until the 7th. Frost this time did not extend farther south than the Ohio Valley, but it is seldom that the area of frost extends

[1] Weather and Climate of Chicago, p. 43.

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into the Southern States, while the center of the HIGH remains over the Great Lakes region; and as the HIGHS usually take the course over the Lakes region in May, it is rare that frosts occur in the South during that month. During the first week of May, 1910, frost occurred as far east as Albany, but it did not reach any of the coast stations. The succeeding HIGH which appeared in the British Northwest on the 10th and moved southeasterly over the Great Lakes region was accompanied by general frosts along its track that extended as far south as Tennessee, even, but did not cause frost farther east than Albany, the coast stations again escaping. These sections are favored partly because of the water influence and the normally higher temperature, and also because the HIGHS when they leave the Lakes move southeast to the South Atlantic Coast States instead of eastward across New England, with the attendant temperature modified accordingly. As a HIGH moves eastward, the southern limit of frost usually extends farther and farther northward, so that frost seldom reaches the Atlantic coast, even of New England, except in pronounced types. The southern boundary of frost generally lies in a southwest-northeast direction.

Occasionally a HIGH advancing eastward from the Great Lakes in the spring or fall will be of sufficient magnitude to cause severe frosts generally throughout New England and even in the Middle Atlantic States. But it will be found that such HIGHS have been centered either in the northern Great Lakes region or over Ontario and in their easterly or southeasterly movement reach the coast with their centers no farther south than New Jersey. The direction of movement of these HIGHS must be determined from the "A" chart and the pressure-change chart. Such types are shown by the weather maps of April 15–17, 1908, and September 13–15, 1911. The middle of April, of course, is not late in the spring for frosts in southern New England, but the middle of September is early in the fall for such occurrences. However, they very seldom occur there as late as May 1 in the spring, but in rare instances these frosts overspread all New England later than that date, even extending southward across the Middle Atlantic States, and such a condition was noted during the passage of a HIGH on May 12, 1907. The course of the HIGH is shown by the maps of May 10–12. (See figs. 117, 118, and 119.) As this HIGH advanced across the Great Lakes region, it was accompanied by exceptionally cold weather for the season, several stations reporting freezing temperature. At the same time the barometer was falling on the New England and Middle Atlantic Coast States, which served to pull the cold air directly across those States, although with diminished intensity.

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The temperature in a HIGH is a most important factor, and if it is unusually low as the HIGH advances eastward, severe conditions may be anticipated over a considerable area, especially when the barometer is falling in its front, or the LOW is already rather deep.

The frosts which occurred in New England the middle of September, 1911, referred to above, were attended by a HIGH which was centered on September 13 over the northern Great Lake region and Ontario and on the 14th over the North Atlantic States. (See figs. 120, 121, and 122, weather maps of Sept. 13, 14, 15, 1911.) This HIGH in its passage across the Lakes, because of previous warm and wet weather there, did not cause any frost in that section except in the extreme northern portion. However, the temperatures were low in Ontario and, as the HIGH advanced, the cold air was pulled across New England where no rainfall of consequence had occurred. This is one of the few instances within the records of the Weather Bureau when general frosts were noted in New England at an earlier date in autumn than in the North-Central States.

Frosts in Rocky Mountain region and adjoining sections.—The maps of May 16–17, 1910 (see figs. 123 and 124), are typical of the conditions which cause general frost in the spring in the eastern foothills of the Rocky Mountains and adjoining sections. The maps of May 21 and 22, 1910, also illustrate the type. In this type the LOW is centered either in the southern Rocky Mountain region or the far southwest with the HIGH in the northwest, generally west of the Rockies. The HIGH in this case is drawn southward and does not ordinarily move to the Great Lakes region, although, as a matter of fact, the one in the second series referred to above did eventually reach the Great Lakes. These HIGHS which move in the spring across the Great Lakes region increase in magnitude and spread out in all directions, westward as well as eastward. The maps of May 25–27, 1910, are typical of such development.

The autumn type which brings frosts to the Rocky Mountain region and adjacent sections is well represented by the series of maps from September 23–26, 1908, referred to on a previous page in connection with North Pacific coast types. (See figs. 107–110.) The cold air was pulled directly across the plateau and elevated sections of the country because of a LOW which was centered in the Rocky Mountain region on the 25th. The *trough* extended thence southwestward to southern California and northeastward to Minnesota. As the HIGH moved southeastward severe frosts occurred in the Rocky Mountain region and adjoining sections, extending eastward over the Plains States and central valleys and southward as far as central Texas. The condition was unusually severe for the season in the mountain States as well as in the far Northwest, where the HIGH first appeared.

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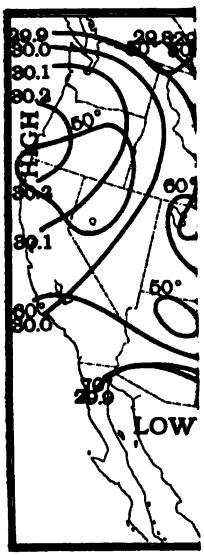

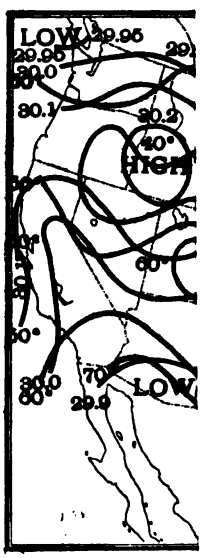

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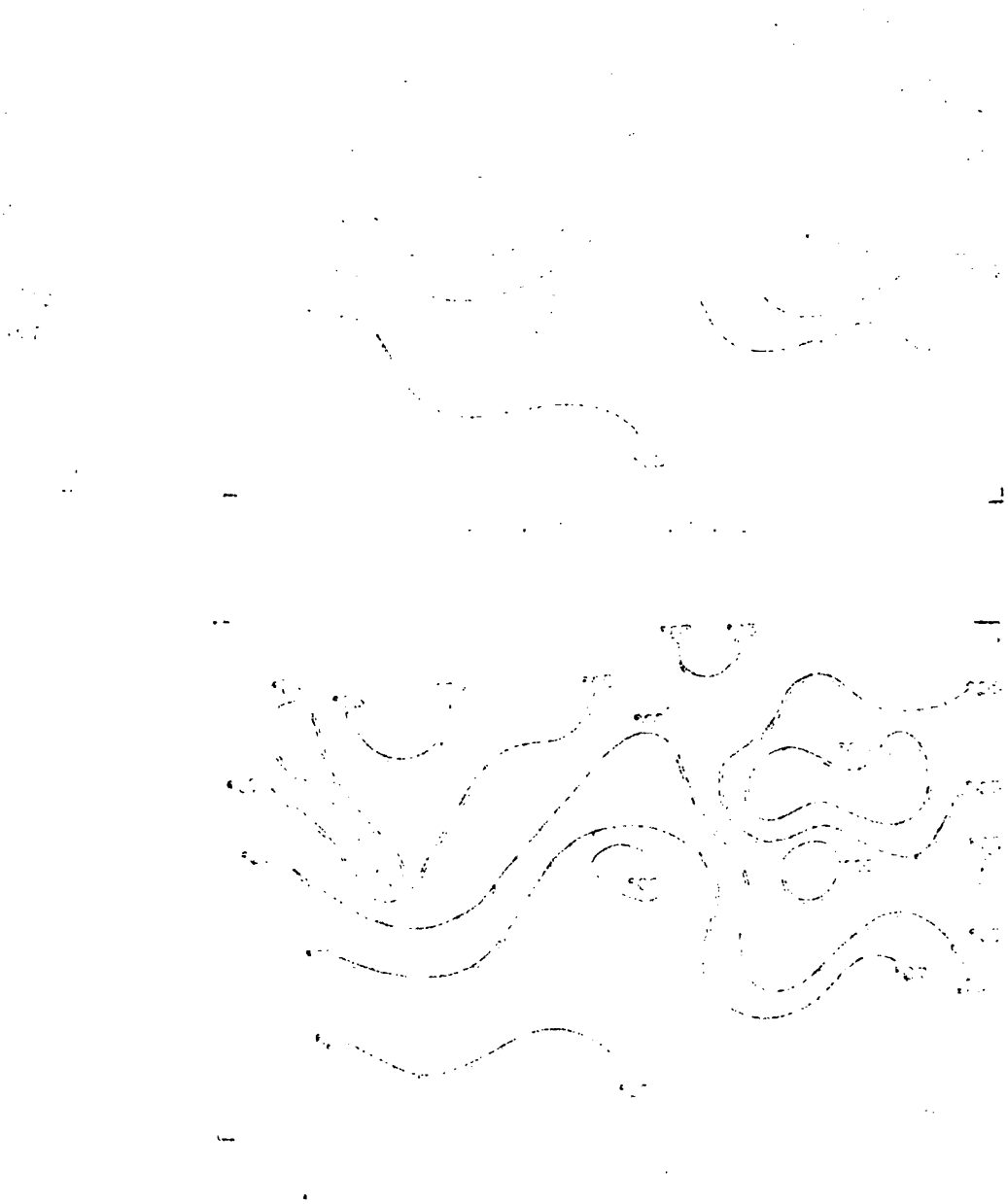

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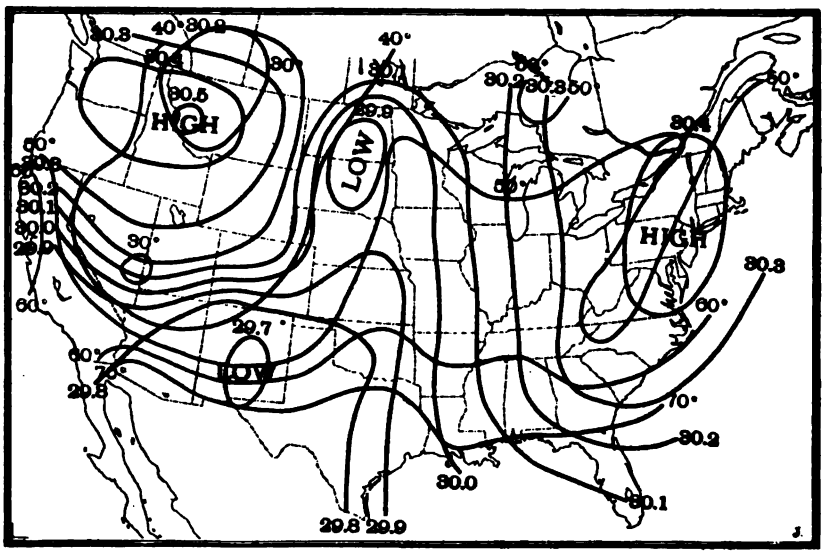

FIG. 123.—May 16, 1910, spring frost in Rocky Mountain region.

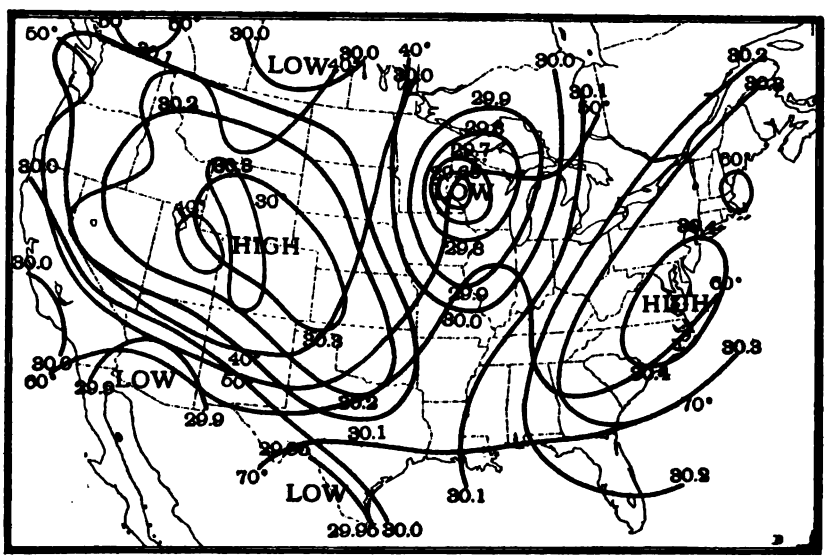

FIG. 124.—Weather map, May 17, 1910, spring frost in Rocky Mountain region.

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Frost in the spring of 1907 and 1910, respectively.—Much the same conditions as those described in preceding paragraph regarding the spring of 1910 prevailed in 1907, and a study of the weather maps during this period should prove interesting and instructive. March, 1907, was unusually mild and at the end of the month the season was from two to four weeks in advance of the normal throughout the central valleys and the Southern States. During most of April the temperature over the agricultural sections of the country averaged abnormally low, this condition continuing into the middle of May. Freezing weather and damaging frosts were reported quite generally during this period over the great central valleys, and light frosts occurred as far south as Arkansas, Tennessee, and the interior of the Middle Atlantic States as late as the second decade of May.

Frost in Wisconsin in summer.—The weather maps of August 7 and 8, 1904 (figs. 101 and 102), illustrate the occurrence of killing frost in summer in the Wisconsin cranberry bogs. (Weather Bureau Bulletin T., p. 15.) In the Massachusetts and New Jersey bogs damage from frost in summer is almost unknown, and at other seasons of the year is less likely than in the higher latitudes of Wisconsin.

Movement of highs in spring and autumn.—The series of maps from May 4 to May 12, 1913, are typical of HIGHS that are attended by frost in the Northern States. In the first part of that period frost occurred in the foothills of the Rockies as far south as New Mexico, but in the easterly movement of the HIGH, the southern limit of the frost area, as usual, seemed to withdraw farther and farther to the north. On May 6, Dodge City, Kans., was the southern limit of frost, and on May 7, Springfield, Ill. The first HIGH was reinforced by another of considerable magnitude, which moved from the far northwest directly southeast over the Great Lakes region to the South Atlantic States, bringing with it frosts in the eastern mountain districts as far south as Asheville, N. C., but on the coast no farther south than New York City. It is especially interesting to note the progress of this HIGH. It approached from the Pacific and moved easterly across the Rocky Mountains and the Plains States to the Great Lakes region where it remained, spreading out and extending eastward, while another HIGH appeared in the British Northwest, which later joined with the first HIGH over the Great Lakes region.

The HIGHS in spring, as stated previously, usually move from the northwest direct to the Great Lakes region and then turn southerly toward the south Atlantic coast; at least this is the normal movement after the middle of April. The HIGHS in autumn, however, move from the northwest directly southeastward over the eastern slope of the Rockies and the Plains States to the South Atlantic States, the centers seldom being as far north as the Great Lakes.

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The weather maps of October 26–28, 1914, illustrate a typical autumn movement, the HIGH being centered in western North Dakota, Oklahoma, and the east Gulf States on three successive dates. Damaging frosts occurred during this period in practically all sections east of the Rockies except near the Gulf coast. Because of the more southerly movement of HIGHS in the fall, the frost condition is likely to be more general east of the Rockies then than in the spring; that is, the southern limit of frost is likely to extend considerably farther south. However, the autumn frosts are, as stated previously, not nearly so serious as those of spring, because most of the crops have been harvested by the time of the fall frosts, and crops, even when exposed, are practically mature, so that a lower temperature can be withstood without injury.

The series of maps from October 8 to 13, inclusive, 1906, illustrate an excellent type of a cold HIGH, starting from the northern Rocky Mountain region and advancing eastward across the country in the rear of a well-marked LOW. The HIGH was of considerable magnitude, but of varying barometer level in its movement eastward. On the 9th the pressure at Miles City was 30.56 inches, and upon reaching the coast sections on the 13th readings as high as 30.62 inches were recorded, but lower on the intervening days in the Middle West. The attending temperatures were abnormally low for the season, and frosts occurred in practically all sections east of the Rockies, with the exception of the extreme South; in fact, frost was noted at Shreveport, Vicksburg, Montgomery, Macon, and at all Atlantic coast stations from Charleston northward.

THE FORECASTING OF FROST.

The successful forecasting of frost depends upon the success in estimating the movements of HIGHS and LOWS with their attendant conditions, just the same as in forecasting weather and temperature. The task of forecasting frost is, one might say, supplementary to that of predicting weather and temperature because the actual occurrence of frost depends upon the temperature and the weather as well.

The positions of the cold HIGH and the LOW must be considered and the future course of each carefully estimated, so as to determine the effect of the HIGH on any particular locality. To bring the frost to any place there must usually be an indraft of cold air from the north and northwest to that point. For instance, frosts, extending southward over the Pacific coast States to southern California, occur chiefly when a HIGH is present over the North Pacific coast districts and a LOW in the south; just so, in order to produce frosts over sections farther east in the Plateau and southern Rocky Mountain

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region, there must have previously been a LOW to the south and a HIGH in the north, west of the Divide. Farther east, in the west Gulf region, for instance, the pressure must have been low and later displaced by a cold HIGH from the northwest. For frost to occur over the Florida peninsula, there must have been a LOW over the southern portion of the middle Atlantic serving to cause an indraft of cold air from the west and northwest. In each of these cases, it is a question of the magnitude of the HIGH as regards both its pressure and temperature and the intensity of the LOW and the barometric gradient as to how low the temperature will fall and how serious the frosts will be.

The intensity of the LOW is almost as much of a factor as that of the HIGH, but, nevertheless, the barometer in the HIGH is ordinarily considerably above normal in the northwest where it starts, registering at least 30.4 inches. In the LOW preceding the HIGH, the temperature is generally above normal and there must be a considerable gradient between the LOW and the HIGH for the transference of sufficient cold air to reduce the temperature in the front of the HIGH to a low point. This is, of course, a question of gradient between the HIGH and the LOW, regardless of the actual intensity of either, although, as stated before, these HIGHS are usually of considerable magnitude. The principal fall in temperature occurs in the district where the LOW was previously centered, but the temperature may not reach the critical point on the first night because of preceding high temperature, or because of wind or clouds. Where the preceding temperatures have been comparatively low the critical temperature is, of course, more easily reached. The farther south the LOW extends, aside from other considerations, the more sweeping will be the cold; just so, if the HIGH takes a southerly course.

The magnitude of a HIGH often varies in its easterly or southerly movement, more often decreasing than increasing, not including, of course, the HIGHS of the Great Lakes region in the spring, which are in a class by themselves. There are many instances, also, where a HIGH decreases and later increases in magnitude. Frosts are most likely in the central portions of a HIGH; for instance, if an isobar of 30.4 inches represents its highest pressure, aside from other considerations, frost is more likely within this line and in the sections immediately surrounding. South and southwest of the main HIGH, where the winds are from the northeast, frost is less likely; while to the northward the occurrence of frost depends upon whether a shoulder of high pressure extends in that direction, causing west or northwest winds there. If a HIGH moves so far to the south that the winds in northern sections are from the southwest, frost is not likely in those sections unless the temperatures are low enough in the HIGH to cause frosts within its immediate area, and so New England often

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escapes frosts because of the southeasterly movement of an interior HIGH to the South Atlantic States. The cold brought in by a HIGH which takes a southerly course is more general, as stated above, but, nevertheless, not so severe in northern sections, unless a ridge of high pressure reaches northward from the main HIGH in the South. Frost is more likely in a district if the center of the advancing HIGH is located to the northwest, but no hard and fast rule can be given, as there are so many complications. The pressure-change map usually shows the direction of movement of the HIGH, the center moving to the place of greatest rise during the last 12 hours, but there are many exceptions to this rule.

In predicting frost the forecaster must consider, as the HIGH approaches, its rate of progress and whether it will be followed immediately by a LOW. A HIGH which moves with great rapidity is not generally accompanied by frost, as the attendant low temperature is usually of short duration; if a LOW immediately follows, frost will not occur to the left of the center of the HIGH. If the HIGH moves slowly, has considerable volume, and reaches out in all directions from the center, the frost is likely to be extensive and to occur on two or more nights. The recovery to higher temperature on its western periphery will not be so rapid as when a LOW immediately follows. The question of frost is, of course, naturally associated with wind velocity, and it is probable that frost is severe in a HIGH of great magnitude, chiefly because its natural concomitants—light winds, dry atmosphere, clear skies, and relatively low temperatures—give the maximum losses of heat from the ground and vegetation, by radiation, and consequently a fall in temperature during nighttime to a point below freezing. Sometimes frost is noted when the pressure is not much above the normal, but this is only when the ground is cold, due to previous low temperature. The possibility of frost depends closely upon the temperature of the soil, and during the spring and autumn when the soil is cold, or in the winter in the extreme South, frost occurs under conditions of pressure and temperature that would not produce frost in the warmer months of the year. So, also, frost never occurs on the first and seldom on the second night following a protracted warm spell, even though the break in temperature is quite pronounced. After a heated period it takes one or more cool nights before the soil is cold enough to permit frost to form. The temperature of the soil is most important and close attention should be given it in connection with the occurrence of frost. So, the previous weather conditions, as affecting the temperature of the soil, must be taken into consideration in the forecasting of frost for any particular locality; and the subject of moisture of the soil must not be overlooked. If the soil is saturated from previous heavy rains frost is quite impossible.

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If the weather can be correctly forecast, it is a short step to the successful forecasting of frost. Not only must the current temperature be considered, but also the humidity. If the temperature is already low, the fall to the critical point will be effected more easily. If the air is humid, the loss of heat through it will be slow and ordinarily frost will not ensue. The character of the sky is most important, and unless the night is clear, or at least partly clear, frost is not possible. Likewise, frost does not occur during windy weather even though the winds may be blowing from the north and northwest, but the temperature during a cold wave may fall to freezing or below on a cloudy, windy night. A previous wind from some point between north and west, preferably northwest, is most favorable for the occurrence of frost. If the conditions are unsettled in any particular region between the LOW and the HIGH for which we are considering the issuing of frost warnings, we must determine whether the wind will decrease and the sky clear by night, although, of course, as stated before, cloudy and windy weather during the daytime is favorable for the occurrence of frost in the ensuing night, because under such conditions the soil is not heated in the daytime, but cooled instead.

We must use the helps in this work that we use in forecasting temperature, and we must also have in mind what the minimum air temperature will be during the ensuing night. The temperature, of course, will vary greatly with the occurrence of light and heavy frost in various portions of the country and even in different sections of the same State. Each cold HIGH has certain characteristics. If the weather in the HIGH is cloudy the probability of frost is not great; if, however, the weather in the HIGH is clear when it appears in the far northwest and is attended by frost, this condition is likely to occur in the sections farther east as the HIGH advances across the country. We must, however, allow for the fact that the temperatures are normally lower in the northwest east of the Rockies than in eastern and central portions of the country, even at the same latitude. A HIGH, as it moves eastward or southeastward, will pass over districts having a higher and higher temperature and the minimum temperatures will not be so low as in the far northwest. Occasionally frost is noted in the summer time in North Dakota and Montana, for instance, that does not later extend eastward, but if a HIGH with barometer readings greater than 30.2 passes over Wisconsin, it is likely to cause frost in the moorlands of that State, even in midsummer. The subject of frost in moorlands is especially discussed in two papers at the end of this chapter.

In the elevated sections of the West, frost is sometimes not noted, even with the temperature below freezing, because of the dryness of

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the air, while in other sections it forms when the temperature of the air is considerably above the freezing point.

Variation in night temperatures and observations of frost.—Night temperatures vary tremendously, often within a small area, depending as they do so much upon the vegetation, the character and moisture of the soil, the humidity of the section, proximity to cities or even buildings, the configuration of the country, proximity to water surfaces, and many other reasons. The temperature varies greatly at Weather Bureau stations in various localities, often because of the difference in exposure of the instruments; the minimum readings at stations having a sod exposure are apt to be much lower on still, clear nights than at stations with roof exposures. A glance at the morning weather map during the passage of a cold HIGH over the country easily distinguishes the stations of the Weather Bureau which are located in the business sections of large cities from those which have an exposure in the country. On any clear, cool night the minimum readings at Charles City, Iowa, for instance, are always 8° to 10° lower than those at Des Moines, Iowa, and usually lower than those even at St. Paul, some distance to the north. (See discussion under cold waves, p. 152.) These temperatures are only relative, and frost may be reported from a station with a minimum temperature as high as 50°, as has been done at Chicago and other large cities, and yet not be observed at other places with readings as low as 36°, particularly in the arid or subarid regions. Of course, frost may sometimes form and be so light as not to be observed.

Usually, however, in sections east of the Rockies, a light frost, at least, is observed at a Weather Bureau station or in the vicinity on clear, cool nights, with not much wind, when the minimum temperature reaches 40°. Whether a frost is reported as "light," "heavy," or "killing," depends upon the judgment of the observer. What one man might consider a killing frost, another might report as "light," and vice versa. There has been, in fact, a wide range in temperatures at which killing frost has been reported at the various stations, and sometimes even in the same cold spell one station will report a killing frost with a temperature higher than at another station where only a light frost is observed. Killing frosts have been reported from Chicago with a minimum temperature at the station as high as 41°, but usually the temperature is close to the freezing point. It is easy to understand how it is possible for a killing frost to occur in the residential sections of a large city on a night with the recorded temperature at the station no lower than 40°, when it is taken into consideration that on clear, quiet nights the temperature of the air on the outskirts of the city is often from 10° to 12° lower than that observed at the station, and that the temperature of the vegetation is several degrees lower still.

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Warnings of frost may be applied locally, depending upon the various physical conditions of topography, soil, vegetation, drainage, etc. It may be safely assumed that on a clear, quiet night the temperature will be several degrees lower on the floor of a valley than on the slopes, particularly if the valley is mostly inclosed. It will be somewhat lower even in slight depressions than on level surfaces. The temperature will be much lower where the vegetation is dense and the drainage poor than over a clean and dry soil; and lower over a peat or black soil than over a sandy one. These factors must be taken into consideration in the practical application of frost warnings, and the forecaster should indicate as far as possible the bearing the warnings may have upon any special conditions. Knowledge as to the stage of growth of crops and the critical temperature during the various periods of growth is also important.

In the issue of frost warnings the weather map, of course, is of prime importance. It should be remembered, however, that the temperatures placed upon the map are mainly from city stations and that they do not indicate the temperature in the open country, especially in the moorland and valleys. Forecasters must allow for great differences and must study their various sections closely in order to determine how large these differences are. This has been done to a great extent through the establishment of stations known as "key stations," which report to the district center by wire once and sometimes twice daily. Frequently the differences in air temperature between these key stations and the city stations are as much as 15° or 20°. Then further allowance must be made for the still lower temperature of the vegetation.

The most perfect local conditions for the occurrence of frost are a cloudy day, preferably with light rain; a fresh wind from the northwest; clearing at sunset with the wind subsiding; rising barometer, with the pressure two or three-tenths of an inch above the normal; previous weather conditions such that the soil is cold, but not because of heavy rains; the maximum temperature at least 10° below the normal for the season, and the humidity ranging from 50 per cent to 75 per cent. It may be considered that frost is quite certain to occur under these conditions, provided a cold HIGH with extensive frosts is centered to the west or northwest of the locality and advancing with average rapidity.

The median temperature and the ensuing minimum.—A help in the forecasting of the ensuing minimum is suggested by Prof. J. Warren Smith in the Monthly Weather Review for October, 1914, by what he terms "A method of determining the median." His plan provides that under conditions favorable for radiation the hour at which the median temperature occurs—the half-way point between the maximum of the afternoon and the minimum of the ensu-

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ing morning—be determined. Following this hour in the evening. the fall thence to the ensuing minimum will equal the fall in temperature from the maximum to the median. For instance, if the median at any place is found to occur at 7.30 p. m., and the temperature at that hour has fallen to 46° from a maximum in the afternoon of 60°, it would be safe to figure on a still further fall of 14° through the night to the freezing point. This method seems reasonable, but, of course, it is likely to be affected by complications. Prof. Smith's remarks may be found in the Monthly Weather Review above quoted.

Relation between the dew point and minimum temperature of succeeding night.—Mr. P. J. O'Gara, in his Bulletin No. 5, "The prevention of frost injury in the orchards of the Rogue River Valley, Oreg.," publishes a table showing 10 dates in the springs of 1909, 1910, 1911, when the dew point observed at 6.30 p. m. and the ensuing minimum temperature were almost the same, but he does not include the dates when these readings were radically different. In connection with these results it is interesting to note that the observations made by Local Forecaster Drake in the Rogue River Valley in the spring of 1914, following the departure of Mr. O'Gara, did not bear out the latter's conclusions. In fact, it is announced that the observations gave great variation between the dew point and the ensuing minimum temperature, and no harmony between them was shown.

Prof. J. Warren Smith, in connection with observations at 10 Ohio fruit frost stations in the spring of 1914, has investigated the subject of the relation between the minimum temperature and the dew point of the evening before, and he concludes:

> In general, the difference may be great enough to make this method of predicting the probable minimum temperature most unreliable. A study of the daily observations shows that when it is cloudy or partly cloudy in the evening and clears off during the night the morning minimum temperature will always be considerably lower than the evening dew point; on the other hand, if it clouds up during the night the minimum will generally not go so low as the dew point.
>
> When the relative humidity is high on a clear, still evening the minimum temperature during the coming night will be lower than the evening dew point, and when this relative humidity is low the minimum will not be so low as the dew point.

The writer, in his studies in the cranberry marshes of Wisconsin in 1906 and 1907 (U. S. Weather Bureau Bulletin T) arrived at results that harmonize with the conclusions of Prof. Smith, and definitely established that a dew-point reading in the evening is no indication of the ensuing minimum temperature. The old theory that there is a relation between these has been disproved so often that meteorologists and others interested should now fully appreciate the facts.

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The percentage of relative humidity a factor.—The question of relative humidity in connection with the occurrence of frost has not yet been studied sufficiently in various sections, but, as a rule, it is thought that in the greater portion of the United States frost is not likely if the relative humidity the previous evening is lower than 50 per cent or higher than 75 per cent. At Chicago, in a five-year period from 1910 to 1914, inclusive, out of 52 frosts in the growing season the humidity the previous evening at 7 o'clock was below 40 per cent 2 times, between 40 per cent and 50 per cent 5 times, 50 per cent and 60 per cent 15 times, 60 per cent and 70 per cent 14 times, 70 per cent and 80 per cent 11 times, 80 per cent and 90 per cent 4 times, and above 90 per cent once. The highest evening humidity followed by a frost was 93 per cent, April 11, 1910, and on the next morning a minimum of 38° was recorded at the station; while the lowest relative humidity reading followed by a frost was 31 per cent, on April 15, 1913, the ensuing minimum being 39. These figures certainly cover a wide range in relative humidity, and until the subject is studied further the percentages, taken by themselves, have little value in forecasting frost.

Moreover, in the moorlands the night humidities, as previously stated, are almost always high, and in the Wisconsin research (Bulleton T) it was found that frost sometimes occurred on nights when the air was nearly saturated and even completely saturated, the humidity ranging from 95 per cent to 100 per cent. Doubtless in these instances the blanket of moist air was shallow and the air immediately above comparatively dry, so as to permit sufficient loss of heat by radiation through it to reduce the temperature to the freezing point. These values, secured in the moorlands, do not apply, however, to ordinary rural districts.

The periods of the year in which frost warnings are required for various sections.—It is the custom for forecasters to issue frost warnings in California, Florida, and the immediate Gulf coast during the entire year, but in other sections of the country the periods change, depending upon the relative earliness and lateness of the seasons. The forecasters are notified by the local observers just as soon as frost warnings are needed in the spring for the protection of bloom or vegetation, and thereafter warnings are issued throughout the season for any region that may be threatened with frost until word is received in the autumn from the observers that warnings are no longer necessary.

Forecasting of frost for cranberry marshes.—The forecasting of frost for the cranberry marshes has been given special attention by the Weather Bureau because of the very low night temperatures prevailing there and because the majority of the cranberry growers

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usually have means of protection in the shape of a water supply for warding off frost, and they are dependent upon the warnings of the Weather Bureau for the success of their crop. Key stations have been maintained by the bureau for a number of years in the marshes of Wisconsin, Massachusetts, and New Jersey, and these telegraph to the district centers their weather and temperature observations each morning during the critical season. Moreover, the writer conducted for several years an exhaustive research in the Wisconsin bogs, the result of which will be found in Bulletin T of the Weather Bureau, previously referred to, and should be carefully studied in connection with this section.

The conclusions of the research above referred to are reprinted below for convenience of reference.

[Extract from Weather Bureau Bulletin T, "Frost and temperature conditions in the Wisconsin cranberry marshes."]

The natural conclusion from the data presented is that the study of local conditions in the marshes is of much importance. It is apparent that the temperature varies greatly in adjoining bogs and even in different portions of the same bog. During a frosty night damage may result in one portion of a bog and not in another, but serious frosts are usually general and not local. A grower may wish to conserve the water supply if the season is dry and the water low, because if he makes too liberal use of it, means for reflowing may not be at hand later when great danger threatens. In view of the fact that reflowing should not be resorted to any oftener than is absolutely necessary, the forecaster and the grower have between them a problem to solve that is sometimes very difficult. When low temperature threatens it must be first determined whether the night is to be clear, the barometer high, and the wind light. Of greatest importance is the clearness of the atmosphere, as there will be no decided fall in temperature during any night unless the clouds clear away; even passing clouds over a marsh often raise the temperature several degrees. But local conditions seldom determine the condition of the sky. The reasons for cloudiness must be found in the movement of HIGHS and LOWS; and the reasons for such movement are not always apparent on the face of the weather map.

True it is that damaging frosts seldom occur in midsummer. The frost of August 7–8, 1904, figures 101 and 102, was abnormal—in fact, a phenomenal condition. The forecaster should know that such a low temperature is not likely to happen in every July or August, because it is far from being the fact, and it can only occur under circumstances on every side favoring its development. It is therefore a well-marked condition—one that would attract the attention of the forecaster almost instantly as he scans the weather map. Ordinarily HIGHS do not bring frosts to the cranberry marshes of Wisconsin in the midsummer months, even though they are of considerable magnitude, have comparatively low temperature, and move across the northern tier of States.

The temperature of the soil is usually too high during the warm season to permit the formation of frost, and it is quite impossible for it to occur during these months following a day of sunshine. On the other hand, frost occurs easily in the moorlands on clear nights during the spring, early summer, and autumn when the soil is cold. The conditions such as obtained during June 11, 12, and 13, 1906, would not be sufficient to cause frost later in the summer

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after the ground had become warm. In determining whether frost warnings should be issued, not only the weather maps must be studied carefully, but also the temperature conditions in the bogs produced by recent hot or cold spells. The temperature of the soil is an important factor at any period of the growing season, and the reading of the maximum thermometer is of much value, indicating, as it does, in a measure, the amount of heat conveyed to the soil during the daytime. Should the maximum temperature in the shelter be below 70° on any day, and be followed at night by clear sky and light wind, pressure above normal and rising, there is strong probability that frost will follow in the bogs, especially if the pressure reaches a height of 30.20 inches or more and the center of the HIGH passes over Wisconsin or the Lake Superior region. The theory that frost does not follow rain has no foundation. In fact, a day of light rain accompanied by a fresh wind which facilitates evaporation at the surface of the soil is often followed by a frosty night, as evidenced by numerous instances in 1907.

Should it be expected that the minimum temperature at La Crosse or St. Paul will fall below 50°, ordinarily there is danger of damage in the cranberry marshes on any clear night. Severe frosts have occurred in the bogs when the temperature at La Crosse was no lower than 48°, as on August 8, 1904. The temperature "in the open" at the coldest place in the bog must fall below 29° in order that serious damage may occur. Probably a temperature for several hours "in the open" as low as 29° would be serious, but there are many instances of minimum temperatures of 29°, and even 28°, when no frost or resulting damage was apparent.

It is important to determine from the weather map whether the weather will be clear over the moorlands because, regardless of how cold it is in the Northwest and how threatening the conditions, there can be no damage done during the growing season if the weather is cloudy at night; but severe frost may occur early in May before the growing season, and in October after the berries have been picked, on cloudy and windy nights, but no damage can then result in the marshes. A perfect condition for frost in the moorlands exists when a HIGH from the Northwest moves eastward with the center over Lake Superior, sending cool north winds thence over Wisconsin, or when the HIGH settles directly over the moorlands, following a day, or preferably two, of cloudiness, with some rain and wind, provided the clouds clear away and the wind subsides in the evening as the temperature begins to fall.[1] While the study of local conditions is of value—temperature and its rate of fall, wind direction and velocity, humidity and pressure—these conditions may not, during unsettled conditions, assist materially in determining whether the weather will clear and frost occur before the following morning. A strong steady rise in pressure is the best local indication for clearing weather, and without this the weather will probably remain cloudy. While a HIGH moving eastward and southeastward over the Lake region is usually accompanied by clear, cool weather, occasionally the movements of such areas are abnormal and cloudiness persists in the front of the HIGH. A remarkable instance of persistent cloudiness was noted from September 2 to 5, 1905. On three successive days the pressure was high in the Northwest, reaching 30.44 inches at Prince Albert, and accompanied by freezing temperatures. This area moved slowly southeastward, gradually losing force, but nevertheless maintaining low temperatures. On the morning of September 4 the pressure was highest over Mani-

[1] When a HIGH moves rapidly across Wisconsin, the pressure begins to fall and the wind to rise immediately after the passage of the crest. Under such conditions, a falling temperature up to midnight is followed by rising temperature during the balance of the night.

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toba, and frost was general throughout the Dakotas. The weather, however, although cold in the moorlands, never cleared during the entire period. Temperatures were as low as 37° on two successive nights, but by reason of the continued cloudiness frost did not occur in the bogs. A study of the local conditions, aside from the pressure, would not have enabled a person to determine whether it would clear on either of these nights. The cloudy weather covered a considerable area, in fact, several States, and the reason for this condition could not be found in the moorland sections of Wisconsin. Similar instances have been noted in other Septembers. When cloudy weather prevails over a large area in front of a HIGH it may ordinarily be expected to continue, unless there is a steady increase in pressure between the LOW and the HIGH. In case of doubt, special observations should be called for by the forecaster in the middle of the afternoon from the cranberry marshes and a few stations in the Northwest, with special reference to the maximum temperature in the bogs and the probability of clear weather for the ensuing night. It might be well to have an observation of soil temperature included in the reports from the cranberry marsh stations each morning in addition to the data usually telegraphed.

The maps of August 7 and 8, 1904 (see figs. 101–102), illustrate a perfect condition for the occurrence of frost. The cloudy weather during the 6th and 7th had prevented the usual warming of the soil, and the breezy weather of the 7th, through evaporation of the moisture near the surface, evidently caused the soil to become colder. The maximum temperature in the shelter on August 6 was 76° at Mather and Cranmoor, and on August 7 it was 65° at Mather and 67° at Cranmoor. We have already shown what a great effect the temperature of the soil has upon the temperature of the air near the surface during any night, and that in marshes the places covered with dense vegetation, with thick matting of moss or thick growth of vines or ferns, are the ones of lowest temperature, especially if the soil has not been sanded and the drainage is poor. When the soil is largely protected from the sun's heat by vegetation and the initial temperature at the surface is low in the evening comparatively low minimum temperatures must result if the night be clear. The situation is even more pronounced if the previous day has been cloudy, because, as a consequence, the storing of heat in the soil has been interrupted and the point of critical temperature may therefore be reached more readily. The relation between the temperature of the soil and the occurrence of frost is noticeable in that it is practcally impossible for frost to occur in the bogs on the first cool night following a warm spell; but it is likely, if conditions are favorable, on the second night after the soil has become cold. Growers claim—and with reason—that frost almost invariably occurs on the second night of a cold spell; and, even if it does occur on the first night, the frost on the second night is likely to be more severe.

Frost remains in the soil of an unflooded bog until comparatively late in the season, and there have been found instances of frost in the soil in marshes as late as July 4. Usually, however, when the winter flow is taken off in the spring the soil is free from frost. The temperature of the soil tends to gradually increase until after midsummer, and then gradually decrease again. The soil being cold in the spring and early summer and again in the fall, frost is more likely to occur then, regardless of the accompanying conditions of atmospheric temperature and pressure. That is, the ground being cold, frost will occur in the marshes in May and early in June under the influence of areas of high pressure and accompanying low temperature that would be far from sufficient to cause frost during the midsummer months, when heat has been stored up in the soil. The length of the nights is also very important in esti-

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mating the probability of the occurrence of frost, especially during the months of September and October, as the nights steadily grow longer and afford greater opportunity for radiation, without compensating insolation.

The forecaster must have in mind the lowest temperature that may occur in the less-favored sections of the marsh, as it is evident that a wide range in temperature will be found in practically all marshes. Even with the knowledge that the lowest temperature "in the open" will fall below the freezing point, it is not certain that there will be any damage. In fact, as has been stated before, the result of the investigation indicates that the temperature "in the open" must fall 2° to 4° below the freezing point in order to cause any serious damage. But the forecaster need not be the judge of what damage may ensue. It is for him to issue warnings, stating in his forecast the probability of light, heavy, or killing frost, and, if possible, how long the cool condition is likely to last, because such information will often assist the cranberry grower in conserving his water supply. It is very important to know the hour in the evening that the frost is likely to set in, because if it begins to form before midnight the damage to unprotected marshes is certain to be serious, as the period of freezing in that event will continue through several hours till daybreak.

FROST WARNINGS FOR THE MASSACHUSETTS CRANBERRY MARSHES.

[By JOHN W. SMITH, District Forecaster.]

Frost warnings are issued and disseminated for the benefit of the Massachusetts cranberry growers during the season from April 16 to June 30 and from August 16 to October 15. These warnings are based on the data of the daily weather map and those of meteorological observations at Boston and from the special meteorological stations in the cranberry bogs at East Wareham, South Carver, Halifax, Marstons Mills, and Norton, Mass. From a study of the differences in temperatures in the shelters on the bogs as compared with those of the local office of the Weather Bureau at Boston, in connection with the daily weather map, deductions are made as to the occurrence of frost, whether heavy or light. Generally speaking, the minimum temperatures in the bogs range from 15 to 25 degrees lower than the minimum temperatures at the Boston station. In cases of fresh to high winds, particularly when easterly in direction, and on cloudy nights, the temperatures in the bogs do not depart greatly from those at Boston. On nights when the conditions are favorable for frost there are at times marked differences in the temperatures in the several bogs, in some instances amounting to from 6° to 10°. These differences can be attributed to various causes, i. e., wind force and direction, proximity to water, character of the soil, whether sandy or not, condition of moisture of the soil, character of vegetation as to density and height above ground. Of course, in forecasting frosts and issuing warnings there has been no attempt at individual details in the service, but the warnings have been issued to the bogs as a whole. At the present stage of the work it

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is not considered practicable or advisable to do otherwise. After further study of the several problems involved, and more extended experience in the forecasting of frosts in the bogs, it may be possible and even probable to particularize in the warnings.

The conditions that are most favorable to frosts in the bogs are high pressure over or in close proximity to the west or northwest of the section, light to moderate north to west winds or very shifting winds, and perfectly clear sky. As a rule these conditions are nearest to being realized when a HIGH of moderate strength and considerable extent moves down from the northern Great Lakes region or southeast Canada, with cloudless skies and passes slowly over the region of the bogs. These conditions occasionally result from the gradual building up of the pressure in the northern Ohio Valley and thence northward to Canada, the resulting HIGH then slowly drifting eastward over New England. At other times the HIGH is well defined, having traversed a good portion of the northern border country, and indications of frost are timely and well pronounced. Weather maps which present the atmospheric conditions under which frost warnings are issued for several successive nights are those of September 10 to 15, inclusive, 1914. During this period frosts occurred in the bogs on the 11th, 12th, 13th, and 14th. The temperatures were apparently quite uniform in the various bogs, the lowest being 27° at South Carver, and at other stations from 28° to 31°. At Boston the lowest minimum temperature during the period was 45°, on the 11th, and the highest minimum 52°, on the 13th. So far as known the only method of protection from frost used by the cranberry growers is by flooding, and then only when water is available.

WARNINGS OF FROST FOR LOUISIANA, TEXAS, OKLAHOMA, AND ARKANSAS.

[By ISAAC M. CLINE, District Forecaster.]

The information conveyed in warnings for frost and injurious temperatures issued by the Weather Bureau for the West Gulf States is of the greatest importance in connection with the successful cultivation of many crops, and it has assisted materially in the diversification of crops and the development of intensive farming. Relying upon Weather Bureau warnings and protective methods, many tender crops, especially garden truck and strawberries, are pushed to maturity early in the spring and late in the autumn, and in some sections are grown throughout the winter, with a view to using the warnings for frost and injurious temperatures in protecting such crops against injury from unfavorable weather conditions.

Each class of vegetation has a different critical temperature at which damage results, and warnings for frost or freezing only do not suffice for the successful protection of crops, such warnings being

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too indefinite for the needs of the farmer or planter. A warning of an expected change in temperature of only a few degrees, giving the temperature expected to occur, when near the freezing point, is a matter of great importance. To meet these requirements the frost warnings are supplemented by freezing warnings, stating what the minimum temperature will be in the next 24 to 48 hours. The intelligent grower knows the degree of temperature at which different kinds of garden truck will suffer injury, the berry, bloom, and plants will be killed, the sugar-cane stalk will be injured, and the bud and twig of the orange tree will freeze to an extent that will cause a loss of the crop, and when he is correctly advised what temperature to expect he knows just what protection is necessary for that temperature in order to save his crop from injury. He can act intelligently and protect only such crops as are likely to suffer injury by the temperatures forecast, without incurring the unnecessary expense of general protection which would be necessary when the warnings state only "frost" or "freezing." In order that crops may be grown profitably when protection to prevent injury from critical temperatures is occasionally necessary, it is of great importance that the expense of protection be reduced to a minimum, and this can only be done when the degree of temperature expected is indicated in the warning.

Type maps for frost in the autumn are: October 7 and 10, 1905; and November 1 and 11, 1911.

Type maps for frost in spring are: April 15, 1904; April 30, 1907; and May 5, 1898.

Types of maps which should be watched carefully in connection with the issue of warnings for unusually severe freezes in the coast region are: January 7, 1886; February 11, 1899; and February 12, 1905.

FROST WARNINGS FOR FRUIT DISTRICTS IN COLORADO, UTAH, ARIZONA, AND NEW MEXICO.

[By FREDERICK H. BRANDENBURG, District Forecaster.]

Freezing weather in April and the early part of May is not always injurious to fruits, for the crops, due to a consistently cold spring, may be too backward to be injured. But when several weeks of abnormally high temperatures occur in March or April, there is apprehension, because of the likelihood of a cold snap in the early part of May. Owing to the great range in altitude of the different districts, the time of blooming varies greatly, so that even though a cold snap is general the damage, if any, is likely to be local in character.

The frost and freezes of spring and fall in the Rocky Mountain region occur for the most part when a HIGH follows in the wake of a

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LOW; the greatest cold occurring in the western and northern quadrants of LOWS. After high pressure is established, clear skies predominate and a great loss of heat by radiation occurs at night, the amount of such loss increasing with altitude, and being greater after light precipitation. Without recent precipitation there is rarely a deposit of frost. Notwithstanding the fact that the fruit districts, as a rule, are located in sheltered valleys of varying exposures and elevations, the following considerations have been found valuable in connection with the issue of warnings of freezes. It is to be understood, however, that the conditions described are not lacking in intensity or energy. During periods of high pressure when temperature conditions are close to the danger point, altitude, topography, air drainage, etc., are factors which must be given special consideration.

Colorado.—Frost is indicated when localities are coming under the domination of a HIGH in the wake of a LOW central on the eastern or southeastern slope.

When a HIGH is becoming established with clear skies and light winds.

Eastern Colorado.—When a HIGH from the northwest or north moves southward east of the Continental Divide in the wake of a LOW.

Western Colorado.—When the crest of a HIGH remains west of the Continental Divide and a LOW prevails in New Mexico.

Utah.—With the approach of the front of a HIGH in the wake of a LOW moving east, southeast, or southward.

With clear skies following light precipitation during prevalence of a HIGH.

During the domination of a HIGH while a LOW prevails to the southward.

New Mexico.—In the wake of a LOW which has crossed the State.

When the front of a LOW has crossed the Continental Divide in New Mexico or Mexico and a HIGH prevails to the northward.

When a LOW prevails in the vicinity of the Gulf of Mexico and a HIGH overlies the southern Rocky Mountain slope.

Northern Arizona.—The growing season in the northern part of the State is very short and hard freezing is common late in spring and early autumn.

Central and southern Arizona.—Destructive frosts are not common, and when they do occur it is during December and January.

Frost may be expected in the wake of a LOW moving northeast, east, or southeast across the State.

When there is a stationary LOW in northeastern Arizona.

When a HIGH with zero temperatures prevails in Nevada, Utah, and Colorado and a LOW overlies southern New Mexico or Mexico.

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FROST WARNINGS IN THE NORTH PACIFIC STATES, INCLUDING WASHINGTON, OREGON, AND IDAHO.

[By EDWARD A. BEALS, District Forecaster.]

The topography of the North Pacific States is such that frost forms in some localities every month in the year, while in others it seldom occurs during the growing period of vegetation. In localities where frost forms in summer only hardy crops are raised, such as cereals and alfalfa, although in these places garden truck is planted and, after being more or less set back on account of frost, good yields are sometimes obtained. No attempt is made to predict summer frosts in localities where it occurs every year, for the reason that no one at these places makes any pretense of protecting his crops, and all are located in isolated communities where telegraphic facilities are poor.

The only persons in the North Pacific States that protect their crops from frost are orchardists. *These people want frost warnings, and the warnings must be explicit, so they may know whether or not it will be necessary to heat their orchards.* For their benefit the Weather Bureau has localized the frost-warning work in a number of places, and the service bids fair to be of great benefit to these people.

This discussion will treat first of the rules and conditions guiding the forecaster in making general forecasts of frost; and second, of the rules and conditions guiding him in making forecasts of an explicit nature for those who protect their orchards and are thus greatly benefited by the warnings.

The season of spring frosts is from the middle of March to the middle of May in southwestern Oregon, and from the 1st of April to the last of May in the remaining sections west of the Cascade Mountains, from the 1st of April to the middle of May in eastern Washington, and from the 10th of April to June 15 in eastern Oregon and Idaho. Fall frosts seldom are harmful, as the crops are practically all gathered before they occur.

During the forepart of the spring season in all these localities the daily range in temperature is of sufficient amplitude to cause freezing temperatures should the maximum for the day be as much as 10° below the seasonal average. On account of cloudiness, the maximum for the day is often that much below the seasonal average, and the question of whether there will be frost depends wholly upon the stillness of the air and whether the clouds will dissipate before morning. The cloudiness prevailing may be due to an unsettled condition without any well-defined HIGH or LOW within the confines of the district, and when such is the case the air is generally com-

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paratively quiet. It not infrequently happens during such periods that shortly before daylight a temporary clearing takes place, lasting perhaps less than an hour and followed again by cloudy weather for several hours or more. Even such a temporary clearing is enough to cause a damaging frost. The forecaster is almost helpless under these conditions, and the only thing guiding him is his judgment as to whether it will clear before morning or not. If the barometer is low, that alone favors continued cloudiness, and if high, with the surrounding country cloudy and movement sluggish, clouds will probably continue. If the clouds are cumulus, it will clear before morning, and if they are strato-cumulus the danger of a clearing spell in the early morning is very great, and if stations nearby report partly cloudy or clear weather frost forecasts should be issued, qualified in exceptional cases by the statement "if the weather clears, frost will form." Such statements are to be avoided as much as possible, but it is believed where the doubt is great a statement of the foregoing character is better than not to issue the warning.

Weather maps of April 10 to April 13, 1911 (see Figs. 103–106), illustrate practically all the types that are followed by frost in the north Pacific States, and of this series the p. m. maps of April 12 and 13, 1911, are the simplest and easiest to handle. As soon as the distribution of pressure shown on the map of April 10, 1911, appears the forecaster must be on the alert, as it frequently happens that the center of the HIGH will not move north farther than the mouth of the Columbia River, in which case the weather continues cloudy, and while freezing temperatures may occur they will be attended by moderately strong winds with more or less rain, and a freeze instead of a frost should be forecast.

No rule can be given that can be relied upon for forecasting whether or not the center of the HIGH will move north of the mouth of the Columbia River, and upon whether it does or does not depends the great difference between clear weather and rain over a large portion of the North Pacific States. Most of the failures made in weather and temperature forecasts come through misjudging the northward movement of the HIGHS off the north California and Oregon coasts. About the best indication of a northward movement is obtained from the two-hour pressure changes at North Head and Tatoosh Island. If they show a stong rise the conditions are favorable for the further northward movement of the HIGH. The rise at these stations, however, may be temporary and a few hours later a fall may take place which will indicate the presence of a LOW off the Washington coast that will move inland; the HIGH will then retreat to the south and become less important in influencing the weather in this district.

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When the type such as illustrated by the p. m. weather maps of April 10, 11, 12, and 13, 1911 (Figs. 103–106), appears a frost is almost certain, and we then have to consider the preceding weather in the various localities before stating the character of the expected frost. If it has been rainy on the preceding days the frost will be light, although the conditions portrayed by the chart would indicate a heavy frost. If the rainfall during the preceding day has been light, say less than ten-hundredths of an inch, the frost will be heavy. If the maximum temperatures during the preceding two or three days have been above normal the frost will be light, although the chart indicates that it will be heavy. If the maximum temperatures during the preceding two or three days have been below normal the frost will be heavy—perhaps heavier than indicated by the chart—and the forecaster should give these matters due consideration, as they are very important.

Our method of forecasting frost in localized centers includes all the foregoing considerations with the addition of a knowledge of the character of the soil in the neighborhood of the key[1] stations. Where the soil is sandy a greater allowance is made for cooling by evaporation when the preceding days have had a light fall of rain, and a greater allowance in the opposite way is made for the heating up of the soil if the preceding days have been warmer than usual. On clayey soils the balance either way is not so great.

Dew-point readings are telegraphed from "key" stations, and an effort has been made to correlate these readings with different weather types, but so far without success. A full explanation covering this point will be found in Weather Bulletin No. 41, entitled "Forecasting Frost in the North Pacific States."

In making district forecasts for the "key" stations where the work is localized the warning always includes the exact minimum temperature expected the next morning. A report is received from the "key" station before the forecast is made. This report contains the preceding maximum and minimum temperatures, the current temperature and dew point, the direction and force of the wind, and the state of the weather. We thus have exact information regarding the conditions in the locality covered by the predictions, and this alone enables better work to be done than would be possible with reports from regular Weather Bureau stations situated, perhaps, 50 or 100 miles distant. In the case of forecasts based upon reports received from the regular Weather Bureau stations, the fact must be borne in mind that the thermometers at these stations are for the most part located in instrument shelters on the roofs of tall buildings, and an allowance must be made to cover the difference between

[1] See W. B. Bul. No. 41, p. 22.

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a roof and a sod exposure, and a further allowance to cover the difference between the estimated sod exposure and the minimum temperature reached in a field 50 or more miles away. This puts the forecaster in the position of making an estimate based upon another estimate. By having a key station in the heart of the locality covered by the forecasts these two estimates are excluded from the calculations, and all the forecaster has to do is to check up his mistakes, which soon will result in an improvement. No rules can be given for this work, as it consists of preparing a weather map covering every frost. On these maps are tabulated the minimum temperatures, the maximum temperatures for the three days preceding, and the dew point of the evening before the frost occurred. A file of these maps is kept in the forecast room, and is so arranged that any type wanted can be found at a moment's notice. When conditions indicate frost, all types similar to the existing conditions are examined, and conclusions reached based upon what has occurred before.

FROST WARNINGS IN CALIFORNIA.

[By Geo. H. Willson, District Forecaster.]

Conditions favorable for the formation of frost in this district are not unlike those which prevail in other sections of the country, and are generally modifications of the conditions that produce cold waves. The passage of nearly every HIGH over the central and northern portions of the Pacific slope during the fall, winter, and spring causes clear weather with rapid radiation and a fall in temperature, all favorable for the formation of frost. The intensity of the HIGH, the direction of its movement, the initial temperature, shown as it approaches, either along the coast or from the north, depending upon the direction from which it comes, and the weather immediately preceding, are the principal factors to be considered. Marked rises in pressure are more liable to be followed by sharp falls in temperature than are moderate or slight rises. HIGHS moving eastward from the ocean, where the lower strata of the air has been in contact with the warm waters of the Pacific, are not so cold as those moving south from the British possessions. If they move eastward over the North Pacific States, giving slight barometric changes in California, the temperature changes in that State will be slight, and only a light frost, if any, may be expected. If the approaching HIGH causes the temperature to fall rapidly along the coast, it will probably continue to fall to, or near to, the freezing point in the valleys and foothills, with severe frosts, unless there is sufficient wind accompanying the rise in pressure to keep the air well mixed. If this is the case, little or no frost will form. If the HIGH with clearing weather follows closely a period of moderate rain, frost will prob-

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ably form, but the moisture present may liberate enough heat to prevent any serious damage.

The most difficult frosts to forecast are those caused by a drainage of cold air from the Plateau region, with very slight barometric changes, sometimes less than 0.10 inch in 12 hours, which are not shown by the lines on the pressure-change chart. The only way the writer knows of anticipating these is by following the departures from the normal barometer, as follows: Draw a line through the minimum-pressure departure on each change chart; this will show the direction and progress of the path of air drainage. If this path leads from the northern Plateau and Rocky Mountain region southwestward to California, it will give severe frost in California in from 12 to 24 hours after reaching the eastern slope of the Sierra Nevada Mountains. Frost from this condition is caused by a very thin layer of cold air extending only a few feet above the ground, and is generally injurious only to vines and vegetables, the cold air seldom reaching the branches of the fruit trees.

In general, forecasting frost in California is a study of air drainage, except when the conditions are very clear-cut, and then it is a matter of brisk to high northerly winds with freezing temperatures. Sometimes seasons are late and sometimes early, varying several weeks for the same location. Again, one portion of the State may have an early season while another may have a late one, and this may apply to several sections, any one of which may be first one season and last the next. Then the distance and protection from the ocean often causes a difference of several weeks in the blooming and harvesting periods. The above applies to the main valleys and lower foothill sections. When the many valleys are considered, the problem becomes much more complicated.

It is quite safe to say that some crop is blooming and maturing and being harvested every day in the year in California. There is a large section devoted to winter-truck gardening, and the acreage is increasing every year.

Frost warnings may be necessary at any time from the middle of October to the middle of May in the more exposed localities and elevated valleys. There are also many years when injurious frosts do not occur in the fruit districts. Frosts are more liable to cause injury at the time the blossoms are falling, and for a week later, than at any other time. At this period the young fruit has lost the protection of the covering flower and the skin is very tender; after a few days or a week the skin toughens and is better able to resist the cold. Vegetables are also at their tenderest stage just after coming through the ground, for the same reason. Ripe oranges will stand temperatures that will injure the green ones, because their skin is tougher and they have a high saccharine content.

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CHAPTER VIII.

FORECASTING HIGH WINDS.

By EDWARD H. BOWIE, District Forecaster.

[With contributions by Prof. H. J. Cox, Prof. H. C. Frankenfield, District Forecasters E. A. Beals and G. H. Willson.]

General remarks:
Wind systems of cyclones and anticyclones 220
Lows that increase or decrease in intensity 222
Hurricanes 230

Storm winds on:
Atlantic coast 235
Gulf coast 239
Pacific coast 244
Great Lakes 241-248

GENERAL REMARKS.

The forecasting of winds of unusual velocity that affect shipping and other interests is of paramount importance among the duties assigned the forecasters of the Weather Bureau and especially is this true with regard to the forecasting of storm winds on the Great Lakes, the Atlantic, Pacific, and Gulf coasts of the United States and in the West Indies during the summer and fall months, when hurricanes may be expected; since all shipping is guided by advices concerning dangerous gales and hurricanes, and the saving of lives and property depends on the timeliness and accuracy of the warnings. The use of wireless telegraphy in the collection of observations and in the dissemination of storm advices and warnings to vessels at sea and on the Great Lakes has greatly extended the possibilities and increased the effectiveness of the storm-warning service.

The forecasters of the Weather Bureau are required to issue warnings of: (1) Winds dangerous to navigation on the Great Lakes, the Atlantic, Pacific, and the Gulf coasts of the United States; (2) violent winds that attend hurricanes in the West Indies, along the Atlantic and Gulf coasts and in the interior of the Gulf and South Atlantic States; (3) winds of destructive force that attend severe local storms; (4) winds of gale force in interior districts that attend snowstorms and cold waves; as for example, the northers of the western plains, and (5) winds of unusual force when they are expected during periods of heat and great dryness in the national for-

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ests, in order that in the last-named case extraordinary precautions may be taken to guard against the outbreak and spread of forest fires.

The weather map is the basis of forecasting and *practically all knowledge of the behavior of storms, etc.*, has been gained therefrom, yet much information additional to that already published may be had from a systematic study of the files of maps. The impression of one who first contemplates the forecasting of storm winds is one of confusion as regards the probable direction and speed of movement of storms that appear on the weather maps. The experienced forecaster has precepts based on long experience and study that aid him in determining the direction and approximate rate of movement of the storm, *and its increase or decrease in intensity will bear direct relation to the rate of change in pressure in progress.* It is conceivable that, were it possible to have in addition to the data already at hand at the time of the synchronous observations, facts regarding the actual rate of fall or rise in pressure within the area of the cyclone or the anticyclone, the forecaster would have information that would aid him materially. For it is obvious that the cyclonic center *would be moving toward that octant within its area* where the pressure was decreasing most rapidly in comparison with that in progress in other octants. Likewise the high or anticyclonic center would be moving toward that region where the pressure was rising most rapidly. In the absence of such data, the forecaster relies to a certain extent on the average rate of movement, based on a long series of observations, as set forth in Supplement No. 1, Monthly Weather Review, "Types of Storms of the United States and their Average Movements." Necessarily these average movements should be the basis for a forecast of a storm's movement, but other factors, such as pressure distribution, etc., must still be considered. Furthermore, special rules guide the forecasters; a number of which will be found enunciated under the head, "Lows that increase or decrease in intensity," on the pages which follow.

In the issue of warnings of high winds for shipping, the forecaster must consider:

(1) The appropriate time for displaying the warnings; that is, the warnings must not be displayed too long in advance of the coming of the dangerous winds, nor should he wait until the storm is ready to break before giving warning. In the former case vessels, particularly on the Great Lakes, may be held in port unnecessarily; otherwise the vessel might have proceeded in safety to the next port. In the latter case, no time for preparation for the storm is given, and, as is not infrequently the case, the vessels depart without knowledge of the approach of the storm and are caught unprepared. It is much better

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that the warning be displayed too early than too late. Especially is this true with respect to coastwise shipping. Warnings should be lowered immediately after danger has passed. Trans-Atlantic steamers sail regardless of whether or not storm warnings are displayed, but they sometimes alter their courses to avoid possible danger, and vessels on the Great Lakes in ordinary storms are not in serious danger provided they have the protection of a lee shore.

(2) The warnings should always convey an idea as to the intensity of the storm winds likely to prevail. It is not sufficient to state that warnings are displayed in a given region, that a storm is approaching, etc.; the warning should specifically state whether the storm is of great or of moderate intensity and that the winds will be violent or only strong. In cases of unusual severity it is advisable to warn vessels to remain in port.

(3) The character of the weather attending the winds should always be stated, especially if snow and low temperatures are expected.

(4) Winds may be classed as onshore or offshore; it is important that this fact be taken into consideration in the issuing of warnings. An onshore wind of relatively low velocity may often be dangerous, whereas an offshore wind of higher velocity may be favorable for departure, provided the weather is not thick. Especially is this true with regard to the winds of the Great Lakes, as, for example, a strong southwest wind is a favorable wind on extreme western Lake Erie, but on the eastern end it is a dangerous one. The converse is true with respect to east and northeast winds on this lake.

(5) The duration of the blow should also be carefully considered. A short hard blow will not make unusually rough seas, but a continued blow, even though of moderate velocity, will make high seas and a dangerous passage. It has been truly said that it is the height of the seas and not the velocity of the wind that is the danger to sailing craft.

Occasions for the display of storm warnings are frequently readily discernible on the weather map and forecasts of the direction and approximate velocity of the expected high winds are not at all difficult. There are, however, numerous instances in which the pressure distribution is such as to create a doubt in the mind of the forecaster as to the proper course to pursue. Some forecasters will always take the safer course and order warnings on moderate provocation, lest suddenly increased storm development *find him without flags hoisted.* Others will incline toward the opposite side and will take chances against increasing development so long as conditions are not marked. Forecasters who pursue the latter course must always be quite sure of their ground and remember that the coming wind direction will

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often be the controlling factor in doubtful cases; as, for instance, failure to hoist warnings for moderately high west winds would not likely prove serious along the Atlantic coast, while the omission of warnings for northeast winds of no higher velocity would often be decidedly so.

WIND SYSTEMS[1] ATTENDING CYCLONES (LOWS) AND ANTICYCLONES (HIGHS).

In the cyclones of the Northern Hemisphere the wind blows around the center in a direction contrary to the motion of the hands of a watch which is lying horizontally with its face upward. Since the direction of the wind is slightly inclined to the isobars, the inflow is of a spiral nature. The amount of incurvature of the winds is usually greatest in the right front and least in the rear of the cyclone, so that sometimes the passage of the trough is attended by a sudden shift of the wind. The force of the winds is commonly supposed to be directly proportional to the gradient. The center is a region of comparative calm, and the highest winds are usually some little distance from the center, where the gradients are steepest. The direction from the center in which the strongest winds are found usually depends on the positions of the adjacent HIGHS. On the south side of the track of the center of the cyclone the winds veer from an easterly to a westerly direction by way of south, while on the north side they back from an easterly to a westerly direction by way of north.

In the HIGHS of the Northern Hemisphere the wind blows around the center in the same direction as the movements of the hands of a watch which is lying horizontally with its face upward, but away from the center of highest pressure, and thus in an outgoing spiral. As in the cyclone, the winds of greatest force are a considerable distance from the center and where the gradients are steep. Good examples of high winds attending anticyclones are found in the "northers" of the western plains and Texas, and occasionally the Great Lakes and the Atlantic and Gulf coasts are subject to gales from HIGHS.

The Weather Bureau warnings of wind force are expressed in terms of the Beaufort scale, a copy of which follows:

[1] See also Chapters I and II.—Editor.

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Beaufort scale.

Force.	Designation.	Miles per hour.
0	Calm	From 0 to 3
1	Light air	Over 3 to 8
2	Light breeze (or wind)	Over 8 to 13
3	Gentle breeze (or wind)	Over 13 to 18
4	Moderate breeze (or wind)	Over 18 to 23
5	Fresh breeze (or wind)	Over 23 to 28
6	Strong breeze (or wind)	Over 28 to 34
7	Moderate gale	Over 34 to 40
8	Fresh gale	Over 40 to 48
9	Strong gale	Over 48 to 56
10	Whole gale	Over 56 to 65
11	Storm	Over 65 to 75
12	Hurricane	Over 75

GRADIENT VELOCITY.[1]

With the object of determining the relation between the barometric gradient and wind velocity at Washington, D. C., five-year records were used, the 8 a. m. printed maps being employed. The gradient was obtained by taking the distance between isobars as shown on the maps. In cases where there seemed liability of error in obtaining the gradient the data were not used. Light winds, or winds of 1 to 5 miles an hour, were excluded. Extremely wide ranges of gradient were noted with winds of the same velocity, and it should be emphasized that the gradient-velocity relation for Washington is a decidedly loose one, although there is the general underlying rule that the greater the gradient the greater the velocity. The following table presents a summary of observations arranged by velocities. All velocities of over 24 miles are omitted on account of the paucity of observations of such velocities in the five-year record, only eight cases being found. In the first column is given the velocity; in the second the number of observations; in the third the average number of miles between $\frac{1}{10}$-inch isobars; and in the fourth a smoothed average obtained by the use of the well-known smoothing formula, $\frac{a+2b+c}{4}$, the values being given relative weight according to the number of observations.

[1] In Ch. I gradient velocity is defined by the equation

$$V=\sqrt{\frac{rdp}{\rho dn}+}$$

which disregards all frictions and in effect implies the winds follow the isobars. Ignorance of the value of the friction and other resistances prevents us from fixing a mathematical relation between gradient and *actual* velocity.

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Gradient velocity table.

Velocity in miles per hour.	Cases.	Difference between 1/2-inch isobars in geographic miles.	Smoothed.
6	261	241	234
8	234	219	223
10	127	198	202
12	99	178	177
14	67	152	158
16	18	115	139
18	14	136	133
20	12	154	141
22	9	113	131
24	6	113	110

LOWS THAT INCREASE OR DECREASE IN INTENSITY.

When the intensity of a LOW is sufficient to produce winds of gale force, the forecaster has no option but to issue the necessary warnings, but as this condition is the exception and not the rule it remains for him to determine whether the LOW will increase in intensity and make necessary the issue of warnings or actually lose force. Moreover, he must constantly be on the alert to detect new developments, especially of secondaries, in order that no winds arise for which warnings have not been issued. This calls for a careful consideration of the 12- and 24-hour pressure changes; the detection of local wind circulations that are commonly the forerunners of secondaries; a knowledge of peculiar types of pressure distribution that precede the development of LOWS of unusual depth; and, in addition thereto, a comprehensive knowledge of the behavior of the different types of LOWS that appear on the weather map. These considerations are set forth in supplement No. 1, Monthly Weather Review, 1914, some of which are repeated here.

(*a*) Lows of great depth (low barometer level) in the Plains States, the Rocky Mountain, and the plateau regions *usually* lose intensity after reaching the Mississippi Valley or the Great Lakes region, and their movement is then slow. *Similar* LOWS *in the Atlantic States either originate in the South or Southwest or else come from the West as moderate disturbances until the Eastern States are reached.* The western and northwestern disturbances, when they become intense in the Eastern States, are usually preceded by an abnormal pressure fall extending far to the southeast of the storm center. (Garriott.)

(*b*) Usually a LOW that moves to the left of its normal path increases in intensity.[1]

(*c*) Some other LOWS that increase in intensity seem to depend on marked horizontal temperature gradients. A rapid temperature rise

[1] See also discussion on this rule in Chap. V, p. 109.—Editor.

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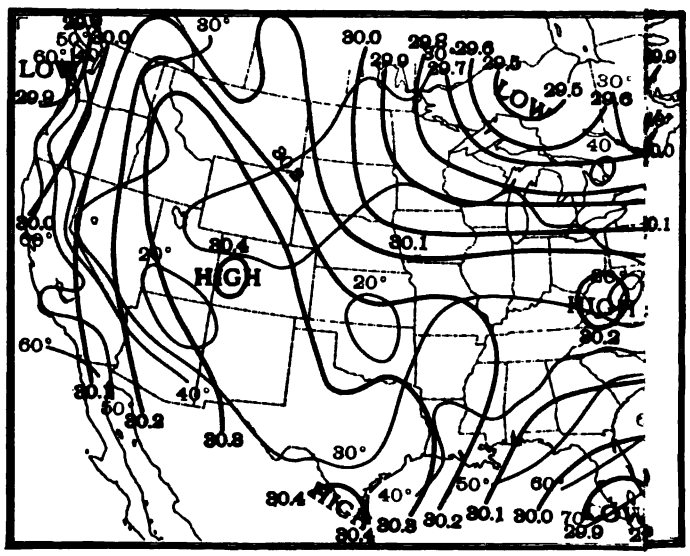

FIG. 129.—November 12, 1904, a.

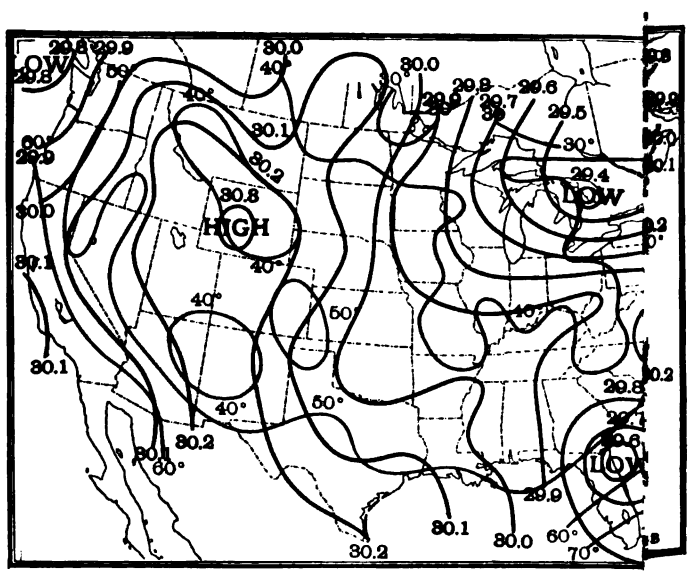

FIG. 130.—November 12, 1904, p.

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in front of a LOW implies an increase in intensity, especially if the temperature is falling rapidly west of the storm center.

(*d*) When the center of maximum 12-hour pressure fall is southeast of the LOW center, the LOW will show a marked increase in intensity. This does not apply to West India hurricanes nor to LOWS of the Southwest.

(*e*) When the area of the 12-hour pressure fall is circular, the LOW increases greatly.

(*f*) A HIGH east of the Mississippi River moving southward or southeastward in advance of a LOW indicates an increase in the LOW's intensity.

(*g*) When the pressure fall is great and the center of greatest fall is near the storm center, a rapid increase in intensity may be looked for.

(*h*) Lows do not increase when there is no precipitation attending them.

(*i*) Lows will not ordinarily increase when there is no extensive pressure fall in the region where the LOW center appears to be.

(*j*) If there is a uniform distribution of temperature—that is, a slight horizontal temperature gradient—LOWS will not increase in intensity.

(*k*) Lows that move southeast generally decrease in intensity.

(*l*) If the *trough* is narrow, there will be no immediate increase; that is, not until the *trough* has widened and the temperature within the same has risen.

Development of lows.—There are several distinctive types of general pressure distribution that presage the development of LOWS of severity, and of these the following are regarded as the most important, primarily because of the fact that at times the appearance of the weather map does not indicate unusual weather conditions.

One of these is characterized by a well-defined LOW in the central valleys, between or slightly south of two HIGHS; one to the northeast and the other to the northwest. (See the maps of Nov. 25, 1895, a. m. and p. m., figs. 125 and 126; Dec. 26, 1904, p. m., and Dec. 27, 1904, a. m., figs. 127 and 128.) In this case the LOW lies south of a belt of relatively high pressure, which connects centers of slightly higher pressure to the northwest and northeast, respectively. This type is usually productive of steep gradients in the northern quadrants. Just as soon, however, as the eastern HIGH increases its distance from the western HIGH, a good pressure fall sets in north of the center of the LOW, thus permitting the LOW to move northward between the HIGHS. The isotherms are generally crowded in the region of and to the north of the center of the LOW and bend well up between the HIGHS. Precipitation, as a rule, is general with this type of LOW.

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The second type is characterized by a ridge of high pressure, extending eastward for a considerable distance from the primary HIGH, which is generally located over the Rocky Mountain region, or the eastern slope. In the examples given (figs. 129 to 133), of which figure 129 is probably the best example, the eastward extension of the HIGH breaks off or separates from the primary and passes to the east or northeast as an independent HIGH, small in comparison with the former. The separation of the eastward extension is generally indicated by the pressure change chart, on which one will probably observe a 12-hour rise in pressure over Tennessee or the Ohio Valley, separated from the main area of pressure rise to the westward. As the eastern or secondary HIGH moves east a LOW develops in the neighborhood of Florida, passes up the Atlantic coast, and in all cases thus far noted becomes an energetic one. This type holds good even though there be no indication of a LOW over the east Gulf or South Atlantic States, as shown by precipitation, pressure fall, or low pressure. The proposition may be generalized somewhat as follows: When any HIGH separates itself from a main or parent HIGH and moves eastward, a LOW develops to the south, or southwest of the moving HIGH.

A number of cases were taken and the average 12-hour pressure fall at the center of lowest pressure southwest of the eastern HIGH was about 0.10 inch. Where there are two or three consecutive 12-hour periods of increase in the distance between the HIGHS, this fall increases on the average up to about 0.20 inch. This type may be found in a number of positions. One case was found where the whole system had been turned counter clockwise, the western HIGH being over the Gulf States and the eastern extension being over New England; while there were some indications of a LOW near Hatteras. A somewhat similar effect is noted when a HIGH passes across the normal path of a LOW that lies to the west of the HIGH and results in an increase in intensity of the western LOW.

The third type is that of the development of a well-defined LOW in the southern end of the trough of a northern LOW. Two cases are considered, depending upon the direction of movement of the primary LOW. (1) When the latter advances along the northern circuit and the secondary develops over the Gulf States, or even the Gulf itself. (2) When the primary advances from the southwest and passes up the Ohio Valley and the secondary develops over the east Gulf or South Atlantic States. In case (1) the secondary develops much farther south of the primary than in case (2). This fact makes it exceedingly difficult to give early warning of the intensity of the secondary. An excellent example of case (1) is afforded by the maps of February 28, 1914, a. m. and p. m., and March 1, 1914, a. m. and p. m. (Figs. 134–137.)

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In connection with this series of maps there was prepared a series of hourly pressure change charts for the region east of the Missis-

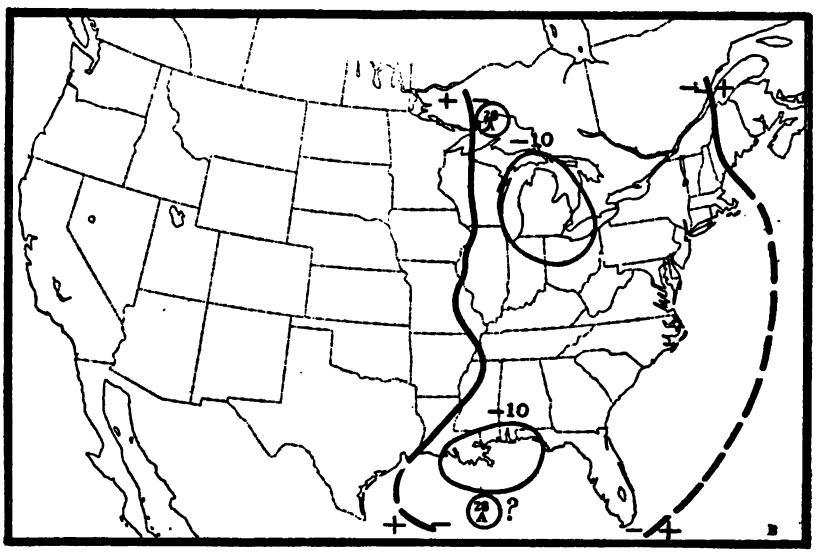

FIG. 138.—Pressure changes 8 a. m. to 12 noon, February 28, 1914.

sippi River, in which the development of February 28 to March 1, 1914, occurred. We have prepared from the data on which the

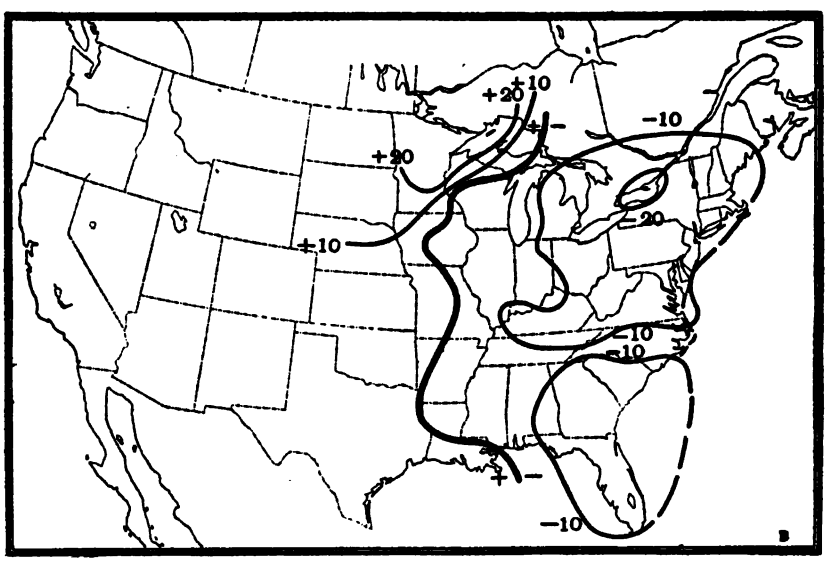

FIG. 139.—Pressure change noon to 4 p. m., February 28, 1914.

hourly charts were based a series of charts, showing the cumulative pressure change for each 4-hour period, beginning with 12 noon of

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February 28, 1914, and concluding with 8 p. m., March 1, 1914. These charts (figs. 138–146) are reproduced below. They show clearly

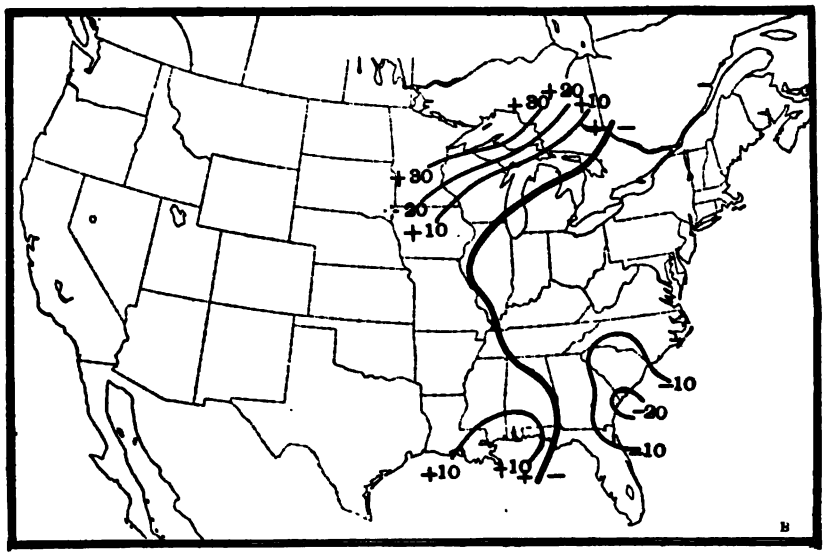

FIG. 140.—Pressure changes 4 to 8 p. m., February 28, 1914.

that the intensity of a LOW, as determined by the 12-hour pressure fall, is sometimes transferred from the northern to the southern end

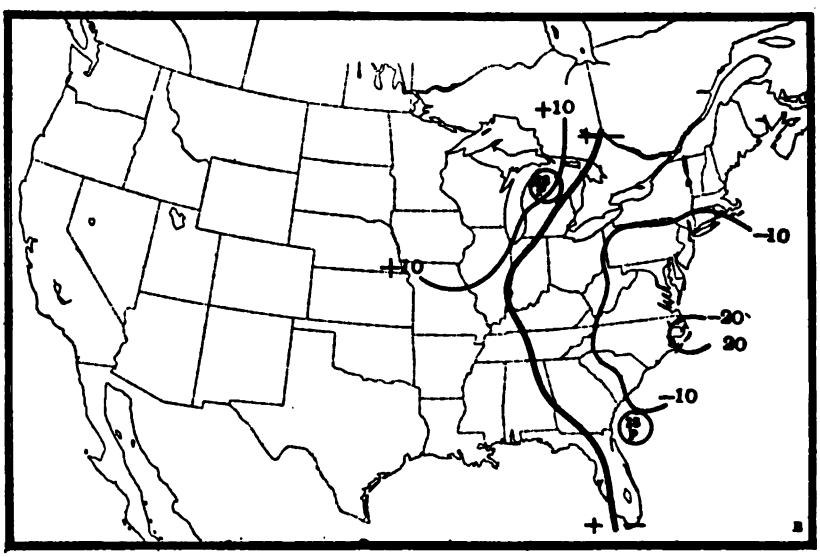

FIG. 141.—Pressure changes 8 p. m. to midnight, February 28, 1914.

of the trough of low pressure that attends the primary LOW. Figures 138 and 139 show that on February 28 the 12-hour pressure fall was

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concentrated in two regions, a northern and a southern, and that in the early afternoon of that date the maximum fall was in the north-

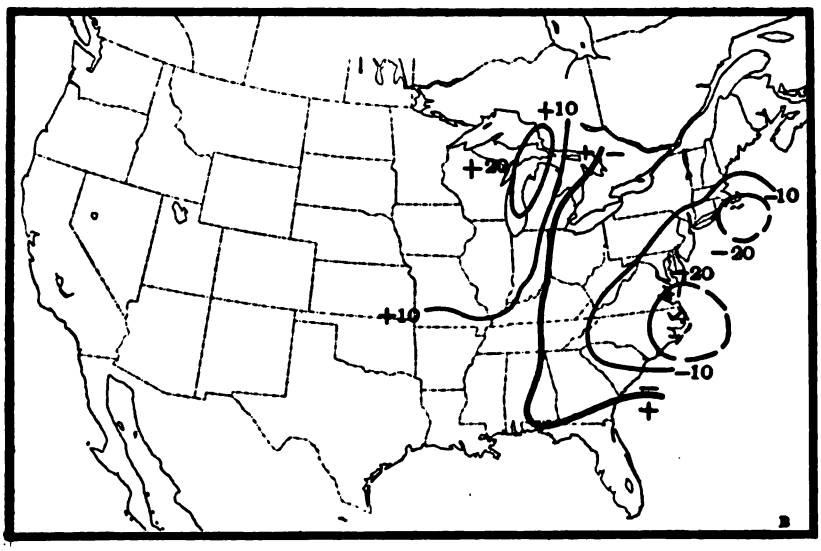

FIG. 142.—Pressure changes midnight to 4 a. m., March 1, 1914.

ern region. The chart for the 4 hours ending with 8 p. m. of the 28th (fig. 140), however, shows the region of maximum pressure fall con-

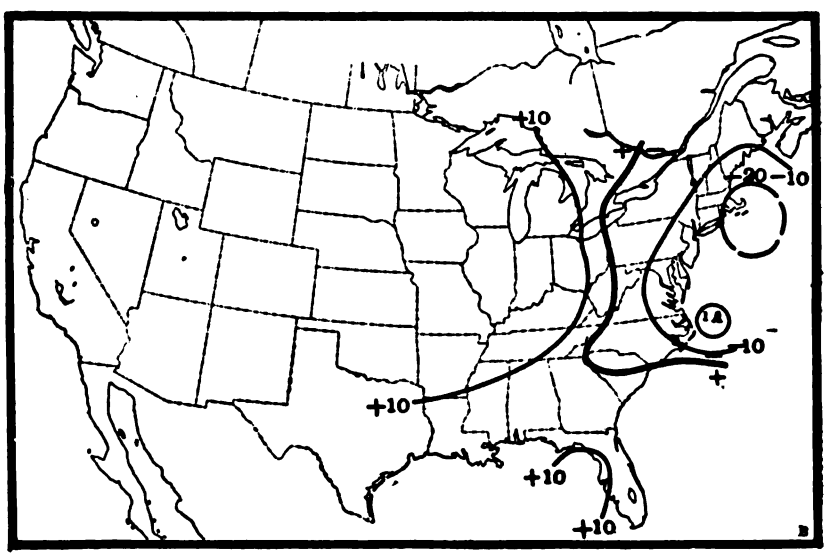

FIG. 143.—Pressure changes 4 to 8 a. m., March 1, 1914.

centrated about Savannah, Ga., and that the fall over the northern district had greatly diminished. Thenceforth the northern LOW

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diminishes in intensity, and what was left of it was absorbed by the southern LOW, as it passed into the field hitherto occupied by the pri-

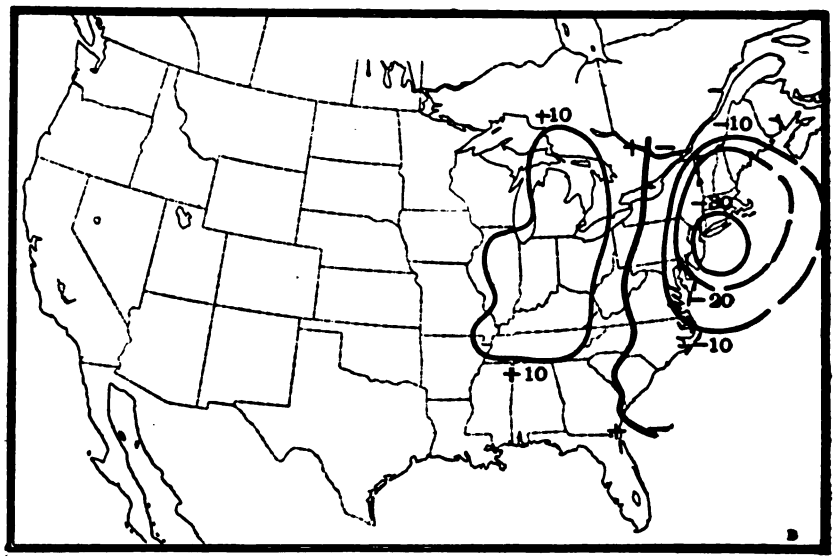

FIG. 144.—Pressure changes 8 a. m. to noon, March 1, 1914.

mary or northern LOW. In the case in question pressure fell along the Middle Atlantic coast continuously throughout the 48 hours ending

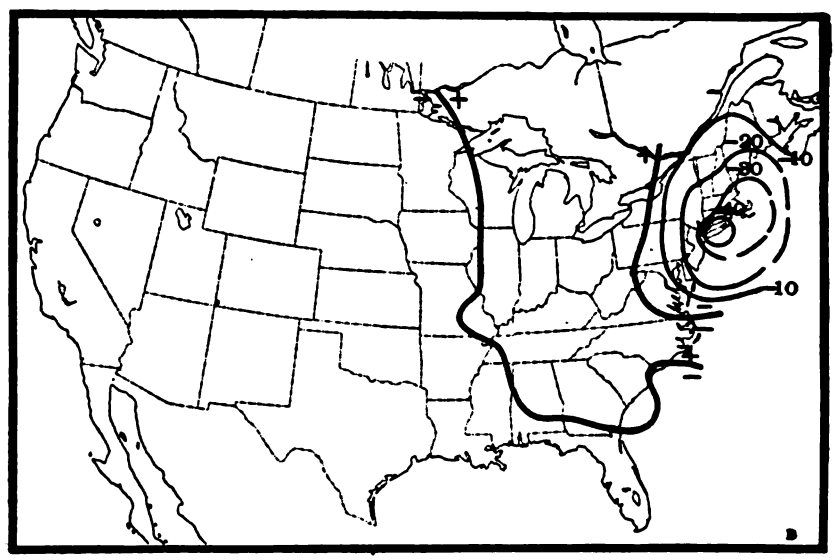

FIG. 145.—Pressure changes noon to 4 p. m., March 1, 1914.

with 8 p. m., March 1, 1914, the total fall at New York and Nantucket being slightly over 1½ inches of mercury. To the phenomenon

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just described the term "swinging trough"[1] is tentatively suggested. Figures 147 and 150 are additional illustrations of the phenomenon described.

The best evidence so far found as to the formation of such a storm is a cyclonic circulation of the wind or a localized 12-hour fall of pressure in the southern end of the trough. If both occur, the secondary will certainly develop. The pressure fall is the earliest indication. The primary LOW in most cases begins to lose intensity, filling up as soon as the secondary begins to develop. In a few cases both primary and secondary developed, but later the primary decreased in intensity and the secondary developed further. This double development was noted only with south and southwest LOWS; that is, in cases

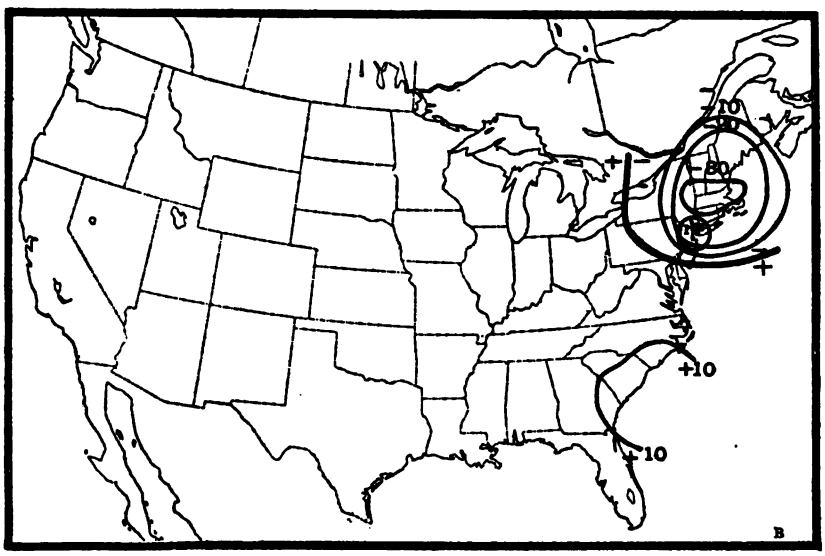

FIG. 146.—Pressure changes 4 to 8 p. m., March 1, 1914.

where both primary and secondary come from the south or southwest. A very important action to watch is the movement of the primary. The best developments take place when the primary moves slowly. If the primary LOW is of northern origin and moves slightly southeastward instead of east, there is a marked development of the secondary in its trough.

Here follow a number of observations on *increasing lows.*

With regard to temperature.—Some LOWS having isotherms crowded and parallel increase materially, and others, having isotherms separated, increase in intensity. Some increase with temperature around them below and others above normal.

[1] Dumb-bell formation has also been suggested.—Editor.

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Relative magnitude of the eastern and western highs.—Lows that increase in intensity in the West generally have the greater HIGH in the East; while those that increase in the East generally have the greater HIGH to the North or Northeast.

Precipitation.—Lows that are not attended by precipitation do not increase materially in intensity. Generally speaking, LOWS attended by general and widespread precipitation will probably attain greater energy than those attended by light to moderate precipitation; that is, we may expect greater developments when precipitation is general.

Pressure fall.[1]—It has been said that if the 12-hour pressure fall is greater than one-half the 24-hour pressure fall, the LOW will increase in intensity. This is hardly a safe rule, because in only about 67 per cent of the time is this true. If we consider only cases where the 12-hour pressure change is more than 0.10 inch greater than one-half the 24-hour fall, this percentage is increased to 73.

With regard to the direction of the center of greatest 12-hour pressure fall from the center of the LOWS Northwest LOWS, as far as observed, give greatest increases in intensity when the maximum pressure fall is southeast of the LOW center. For LOWS in the East, the greatest decreases in pressure at the center result when the center of maximum pressure fall is between north-northwest and north-northeast of the center of the LOW. Possibly this rule might be generalized as follows: Lows increase in intensity when the center of maximum 12-hour pressure fall is ahead of the center of the LOW and on its normal path.

HURRICANES.

The following are extracts from Monthly Weather Review, Supplement No. 1, page 10, under the title "Recurving storms," and are considered the most important rules for the guidance of the forecaster in determining the course of the hurricane.

(1) A hurricane does not move directly toward a region of high pressure when the latter is not moving perceptibly, but follows in behind or around the high. If the HIGH moves over the Eastern States east or northeast off to sea at a normal rate of progression, opening a trough after it, the hurricane moves north or northeast in a normal path. If the HIGH hangs persistently over the eastern coast of the United States, the hurricane is deflected far to the west before it can recurve.

(2) If rain falls freely over the land in advance of the hurricane it is likely to lose intensity after crossing the coast line; if the downpour begins after reaching land, it is probable that a long, vigorous march is yet before it, except those moving westward over the Gulf of Mexico, which usually dissipate after reaching the coast.

[1] See also Chap. IV.—Editor.

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(3) When a West India hurricane is moving westward in the longitude of eastern Cuba, and is north of that island, it will recurve east of the south Atlantic coast of the United States, when a HIGH covers the northwestern States. If the hurricane is moving westward over Cuba or the western Caribbean Sea, when a LOW occupies the northwest and the pressure is high in the Eastern States, it will probably move to the Gulf of Mexico and reach the Gulf coast after recurving.

(4) It may be assumed that with a nearly normal distribution and movement of atmospheric pressure areas over the United States, hurricanes will recurve near longitude 80° and between latitudes 25° and 28° N. When a hurricane is central east of Cuba and a HIGH is advancing eastward over the Gulf and South Atlantic States, the hurricane will probably recurve east of the Bahamas. When the hurricane reaches central Cuba or longitude 80° W., and a HIGH is over the west Gulf and the southwestern States, the hurricane will probably recurve over Florida or the east Gulf. When the hurricane reaches the seventy-fifth meridian, and a HIGH is overspreading the interior and eastern districts of the United States with stationary or falling barometer over the west gulf and southwestern States, it will probably advance westward over the Gulf of Mexico. When a hurricane is moving northwestward toward the south Atlantic or middle Atlantic coasts of the United States, and the pressure is abnormally high over the northeastern States and the Canadian Maritime Provinces, the chances are that the storm will not recurve, but will be crowded in upon the coast and develop destructive energy. (Garriott.)

Espy remarks in his Fourth Meteorological Report that—

> A sudden rise of the barometer, especially in low latitudes, is a proof that there is a storm in the neighborhood, and is one of the first indications of an approaching storm.

Espy considered it a fact fully established that without such a rise no storm of dangerous violence need be feared, but that the converse of it was not true.

Further remarks concerning the movements of cyclones given in Weather Bureau Bulletin A, Summary of Meteorological Observations—Dunwoody, Washington, 1893—and an abstract of an unpublished manuscript by the late Prof. E. B. Garriott follows:

> During the three principal cyclone months, August to October, the storms generally recurved near or immediately east of the Florida peninsula. This is merely an average, however, and many of the cyclones of these months recurved far to the eastward of the Bahamas and others over the Gulf of Mexico. Again a number of the more energetic and destructive storms had no recurve and advanced westward over the Gulf of Mexico. The recurve of storms in the West India and Gulf of Mexico regions is dependent upon the

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general meteorological conditions, and more especially upon the distribution of atmospheric pressure.

The anticyclone or high of the North Atlantic Ocean lies northeast of the West Indies and causes easterly winds over the southern part of the ocean and the Caribbean Sea. The storms that develop in the regions east of the West Indies, and also those of a more western origin, have a tendency to follow the course of the main equatorial current over the Caribbean Sea. This course is doubtless largely influenced by the general drift of the atmosphere in that region, and following the anticyclonic circulation of winds the cyclones skirt the western quadrants of the Atlantic high and follow the course of the Gulf Stream to the middle latitudes. This may be considered the usual course of the West India cyclones when the usual meteorological conditions obtain over the west-central North Atlantic Ocean and eastern part of the United States. In cases where storms that originate near the West Indies do not recurve to the northward but move westward over the Gulf of Mexico high pressure to the northward apparently prevents the recurve. Observation has shown that when the advance of a storm of pronounced strength is forced or held back by a high which persistently occupies the region through which the storm would pass with the prevalence of usual conditions, the storm acquires destructive energy before filling up or dissipating.

Among notable storms of this class may be mentioned the cyclone of August, 1886, which totally destroyed the city of Indianola, Tex., and the cyclone of September, 1888, which raged with destructive violence in Cuba. These storms were apparently unable to recurve, owing to the high-pressure obstruction to the northward. Forced westward, they developed intense energy and dissipated, one on the southeast slope of the Rocky Mountains, and the other over eastern Mexico. An almost entire absence of reports from the region east of the Windward Islands prevented the tracing of storms to their place of origin. It is supposed that storms which advance from east of the Caribbean Sea develop in the region of equatorial rains and are carried thence eastward by the prevailing wind currents. During the period 1878 to 1887, inclusive, no West India cyclones were traced south of the tenth parallel, and the southernmost position occupied by a West India cyclone center was N. 10, in W. 44, in October, 1887.

The velocity of West India cyclones average 18 miles per hour before the recurve, 10 miles per hour during the recurve, and 24 miles per hour after the recurve.

An unpublished manuscript by the late Prof. E. B. Garriott mentioned above deals especially with the details concerning the movement of two West India hurricanes, namely, those of August 17–30, 1886, and August 26–29, 1893. These two examples illustrate, in the one case, a hurricane which does not recurve and, in the other, a hurricane which recurves near the Atlantic coast line and moves northeastward. The weather maps of August 17–20, 1886, and of August 25–29, 1893, are reproduced to illustrate the details of pressure distribution in these two cases. (Figs. 151–158.)

It is pointed out by Prof. Garriott that in the case of the hurricane of 1886 the distribution of pressure, as shown by figures 151–154, was not favorable for a recurve and that in the case of the hurricane of August, 1893, pressure distribution was different in that a LOW

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Fig. 155.

g. 156.—

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occupied the northwestern part of the United States, and that in its eastward movement it developed into a trough of low pressure, so that the northeastward movement of a West India hurricane was facilitated. Detailed descriptions, especially of the 1893 hurricane, appear in Monthly Weather Review, Volume XXI, pages 207–209.

Likewise, a description of the earlier hurricane may be found in Monthly Weather Review for August, 1886, Volume XIV, page 210.

See also a later paper on West India hurricanes, Weather Bureau, Bulletin X, Hurricanes of the West Indies, by Prof. O. L. Fassig. The last named contains a chronological list of hurricanes of the West Indies and charts showing the paths of West India hurricanes for the several years covered and much other valuable and interesting information.

It has been shown that the course of West India cyclones is governed by the distribution of pressure over the United States. When a storm of this class is within 24 to 36 hours average travel of the Florida coast its subsequent course can be closely calculated. It can not recurve in the face of an approaching HIGH from the west or northwest. Therefore when a cyclone is central over or near Cuba and moving in a westerly direction the forecaster should study the pressure distribution over the United States. If a HIGH is approaching over the central valleys and the Great Lakes the storm will not reach the Atlantic Coast States but will recurve east of the coast line or pass into the Gulf of Mexico, and in the latter case it is likely to reach the Gulf coast after the passage of the HIGH. If, however, a LOW appears over the Western States or the Northwest when a cyclone has advanced to the longitudes of Cuba the latter may be expected to reach the United States coasts. The northwest LOW will move eastward attended by a decrease of pressure and, if it possesses sufficient strength, will, in conjunction with the westward moving West India cyclone, dissipate the South Atlantic States' HIGH and form a trough of low pressure which will cover the Eastern States and form a pathway for the passage of the cyclone.

NORTHERS AND BLIZZARDS.

The origin of the northers of Texas and the Gulf of Mexico is discussed at some length in the early numbers of the Monthly Weather Review. (See Vol. 21, pp. 226 and 363.)

Ferrel[1] says of the norther:

It is seen that in cold waves and northers we simply have the usual trough phenomena of cyclones in their passage over a place, where these phenomena are well marked. These, we have seen, occur mostly in winter, and in latitudes where cyclones have an easterly progressive motion and rarely in summer; and

[1] A Popular Treatise on the Winds, p. 327: New York, 1889.

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precisely the same is true of cold waves and northers. In all there are, first, mostly southerly and southeasterly warm and damp winds, accompanied by a gradually falling barometer, which toward the last becomes very rapid. Then comes the dividing line between the warm southerly and southeasterly winds, and the cold northwesterly winds, which, on account of the great difference of temperature, do not readily mix, and so there is a sudden passage from the one to the other. There is, on this line, a very steep pressure gradient for a short distance, which, however, soon passes over, and during this time the squalls are often terrific; after which there are, for several days, the usual westerly winds of the rear of the cyclone.

In the light of the daily weather maps the norther is a strong, cold wind from the north or northwest, which blows on the west side of a well defined LOW when the latter is situated over Texas or the Gulf Coast. The name is due to local usage, before the beginning of daily weather maps; hence it has no very special significance. In California the name has been given to a very warm dry wind that descends to the valleys from greater altitudes.

Blizzards.—When very low temperature is associated with the conditions which produce a norther the resulting phenomenon is popularly known, especially in the Plains States, as a blizzard. The conditions are as follows:

When the pressure is high and the temperature is low over the Canadian Rockies, and a well marked LOW lies to the south with a steep barometric gradient, the LOW will usually move southeast and east and the high will push southeastward with northerly gales, rapidly falling temperatures and some snow, and conditions assuming the proportions of a blizzard will ensue over the eastern slope of the Rockies that are especially dangerous to exposed cattle and warnings should be issued to ranchmen well in advance. (See maps of Jan. 28–30, 1909; Mar. 13–15, 1913.)

Northers in the Gulf of Mexico (Pilot Charts, November).—During November the "nortes," or northers, become established, and occur occasionally all winter. In the earlier months of the season they are of frequent occurrence and long duration, attaining full strength in a few hours, and often lasting two days or more. Later they occur less frequently and are of shorter duration, but of somewhat greater violence. The usual indications are a steady wind from the south, with clear atmosphere in that direction, but with a peculiar haze toward the north, falling barometer, and warm moist, oppressive atmosphere, with a heavy cloud bank, and lightning to the northward. Soon the wind shifts in a heavy rain squall, and the gales set in from the northward, with cold and sometimes clear weather.

In winter a norther is almost invariably attended by a cold wave; hence it is convenient to combine the warnings with those for the cold wave. In the autumn and late spring months, when cold wave warnings are not issued, daily forecasts should contain mention of the occurrence of northers.

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STORM WINDS ON THE ATLANTIC AND GULF COASTS.

By H. C. FRANKENFIELD, Professor of Meteorology.

Along the New England coast.—The most dangerous winds are those from the east or northeast, principally the latter, and it is wise to order northeast warnings as soon as a southern or southwestern LOW comes within 700 or 800 miles of southern New England, provided there is a HIGH, if only of moderate proportions, to the northward. Under this condition a moderate LOW as far south as the lower Mississippi Valley, in winter, the east Gulf coast, or northern Florida, if moving northward or northeastward calls for northeast warnings on the New England coast, as these southern LOWS almost invariably increase greatly in intensity and velocity of progression as they move northward, particularly if pressure at Bermuda is quite high. If the ocean pressure off the south coast is not high, the LOW will probably be less severe. If the LOW is a southwest one, and the middle Atlantic pressure is low, the interior storm center may turn eastward after reaching the upper Ohio Valley and pass off the New Jersey coast. This departure would cause high northerly winds over southern New England, but probably not north of Boston, as the LOW would probably decrease, or at least would not increase in energy after turning to the eastward.

High winds from the southeast are very infrequent,[1] and will not occur except with steep barometric gradients. For this reason southeast warnings should not be ordered unless the gradient on both sides of the storm is very pronounced. If the forecaster feels that he must order a southeast warning, he should include in the warning an order to change the warnings to southwest or northwest within a comparatively short time. It will not be necessary to change to northeast unless a mistake was made in the original order.

High southwest winds are probably the most frequent of all high winds on the New England coast. They occur mainly when a well-defined LOW from the west moves across New England by way of the upper Great Lakes or the Ohio Valley, provided pressure is fairly high to the eastward and southward. The southwestern LOWS are the best type of a high southwest wind producer, as they usually move up the Ohio Valley with steadily increasing intensity, resulting in such steep barometric gradients that high winds must occur. Warnings of southwest winds for the New England coast should usually be ordered when the LOW is over the Province of western Ontario, western Lake Erie, or the Upper Ohio Valley. Should there be a

[1] See the table on p. 239.—Editor.

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strong but yielding HIGH over northeastern Canada or northern New England the winds will not rise to high velocities very quickly, and it may be 15 or 18 hours after the center of the LOW has reached the localities above mentioned before the winds increase materially, swinging first around to southeast and south.

The northwest winds following a decided LOW will also call for warnings; although being offshore winds, they are less dangerous than others. They set in as soon as the center of the LOW passes and the temperature begins to fall, and frequently they will continue with high velocity for some hours after the barometric gradient indicates that there should be a decided moderation. Sharp temperature gradients over limited areas are probably responsible for much of this behavior, and the winds appear to lessen when the temperature gradient becomes fairly uniform.

As a general proposition the highest winds along the New England coast occur between Boston and Block Island, and especially from Block Island to Nantucket. The recorded wind velocities at Boston do not give a fair indication of those prevailing outside the bay, but reports from Highland Light, at the entrance of Boston Bay, which are always available, give the true conditions. Small-craft warnings are of benefit to fishing craft at all seasons and to pleasure craft in summer.

On the Middle Atlantic coast.—The remarks regarding high winds along the New England coast apply almost equally well to the Middle Atlantic coast. Warnings, however, are needed less frequently south of Delaware Breakwater, and at times there occurs a type of storm moving across the South that will necessitate northeast warnings on the Virginia coast, but no farther northward. For storms moving northeastward, Hatteras is probably the southern limit for northeast warnings; warnings for points below Hatteras require southeast to southwest warnings at first, usually the latter. Again, high velocities with the shift of winds to the west and northwest are not so long drawn out as along the New Jersey and New England coasts.

A local peculiarity should be mentioned—that is the tendency at the least indication toward increasing winds on the New Jersey coast between Barnegat and Long Branch. High winds are much more frequent over the northern portion of the Jersey coast than over the southern portion, and between Sandy Hook and Point Pleasant east winds are especially strong. This condition appears to extend from the coast line between Sandy Hook and Point Pleasant eastward as far as the island of Nantucket and probably into the Cape Cod district. The section between Nantucket and Long Branch is known, at least to the New Jersey fishermen, as the "Graveyard of the Atlantic." A pecularity of this strong east

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wind is that it does not extend into Long Island Sound, nor to New York City to any great extent, where the anemometer is more than 400 feet above the ground, nor very far south of Barnegat. At New York City the east wind velocities are not nearly as high as at Long Branch, 30 miles below on the open coast. At Long Branch it is only the easterly winds that are the stronger, while at Block Island and Nantucket both easterly and southwesterly winds are abnormally high. With westerly and northwesterly winds the differences are not so marked, and New York City with the present anemometer exposure will show higher velocities than any other station on the north coast. In general, it may be said that when east winds blow on the New Jersey coast they will be much stronger over the northern portion.

Small craft-warnings are of use along the coast, those for easterly winds especially, to the fishermen along the New Jersey coast. Their nets are kept out in fair winds, but easterly winds whose velocities exceed 20 miles an hour are very likely to tear loose and destroy the nets. If warning is given, the nets can be saved by sinking them below the surface of the water.

On the South Atlantic coast.—As the South Atlantic States are away from the usual storm tracks, warnings are needed much less frequently than along the Middle Atlantic and New England coasts; and along the southern Florida coast warnings of any kind, except an occasional small-craft warning, are very infrequent.

The most important and at the same time the most frequent storm warnings are the northeast ones, the southwest ones ranking next.

Northeast warnings are indicated for the Carolina and Georgia coasts, and occasionally at Jacksonville when LOWS are moving northeastward across the Gulf of Mexico, and they should be ordered as soon as the storm center is over, or south of, southern Alabama. On the other hand, if the center of the LOW is over northern Alabama or even over northern Mississippi, and is moving with fair velocity, northeast warnings should be ordered for the North Carolina and the Virginia coasts. Should a tropical storm be approaching, northeast warnings should be ordered for southern Florida, if possible, when the storm center is 24 hours distant, and they should gradually be extended northward as long as subsequent reports indicate a storm movement toward the State of Florida. These tropical disturbances supply about the only occasion for the display of northeast storm warnings over any portion of the Atlantic coast of Florida. If the storm be a severe one, the northeast storm warnings should be replaced by hurricane warnings as soon as possible, 24 hours' warning of the approach of a hurricane being none too little.

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When northeast warnings are ordered on the North Carolina coast for LOWS moving across northern Mississippi or northern Alabama, southeast warnings, with a view to an early change to southwest, should be ordered for the South Carolina coast, and possibly also the Georgia and north Florida coasts if the disturbance is a marked one. Should there be a slow-moving HIGH over the Atlantic Ocean, the storm coming from the Gulf States, the Gulf of Mexico, or the southern portion of the North Atlantic Ocean will be more contracted and will likely prove move severe than if pressure over the ocean to the northward were lower. However, the LOWS moving northward or northeastward will almost invariably increase in intensity without regard to pressure conditions in front of them, except when there is a very strong HIGH to the northward or northeastward. This distribution will sometimes, although not always, hold a southern LOW in check, and may even cause it to change into an irregular and almost stationary LOW with general rains or snows, but no high winds.

SEA SWELLS.

An important feature in connection with the approach of tropical storms from the southern portion of the North Atlantic Ocean or from the Gulf of Mexico is the observation of the character and direction of the sea swell and also the heights of the tides. A sea swell will often give advance notice of the coming of a storm, sometimes before the appearance of the cirrus clouds, and a long time—sometimes two or three days—before falling pressure and changing wind direction indicate that a storm is coming. Reports of such sea swells are of the greatest importance, and observers should seize every opportunity to make them as frequent and as complete as possible. Abnormally high tides also frequently indicate the approach of a storm, and such occurrences should also be reported. Of course, radiograms of the present day have largely obviated the necessity for such careful reports of sea swells and tides, but they are nevertheless of great importance and assist in confirming information obtained from radiograms.

These remarks apply equally well to the Atlantic and Gulf coasts.

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STORM WINDS ALONG THE ATLANTIC COAST.

The discussion for each of the geographic districts concludes with a table similar to the one below.

Percentage of storm winds from the north, northeast, etc., for each station on the Atlantic coast, 1905 to 1914, inclusive, and verifying velocities (miles per hour).[1]

Stations.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Verifying velocity.
Eastport, Me	4	24	14	14	14	3	16	11	34
Portland, Me	7	6	4	15	11	3	11	44	32
Boston, Mass	6	11	6	4	5	15	28	26	32
Nantucket, Mass	9	26	6	11	8	27	11	3	40
Block Island, R. I	5	15	7	6	3	4	17	45	44
New Haven, Conn	14	10	4	4	12	9	23	24	28
New York, N. Y	6	3	1	3	2	9	22	54	44
Atlantic City, N. J	3	22	4	12	36	4	4	16	28
Philadelphia, Pa	18	7	2	6	6	8	6	48	30
Delaware Breakwater, Del	14	12	5	3	7	13	3	44	40
Baltimore, Md	16	4	2	4	6	14	24	31	26
Norfolk, Va	9	6	1	6	6	29	19	24	36
Cape Henry, Va	36	14	5	1	3	2	8	32	40
Hatteras, N. C	29	8	0	4	8	11	12	29	40
Wilmington, N. C	5	10	5	0	13	37	14	17	30
Charleston, S. C	11	28	18	7	14	8	8	7	36
Savannah, Ga	6	6	11	3	12	12	31	20	36
Jacksonville, Fla	4	5	1	4	17	54	10	6	34

[1] The highest verifying velocity for each storm was tabulated for the period of 10 years for each of the 8 principal points of the compass, one entry only being made for each storm that gave a verifying velocity. The table shows, therefore, the distribution of verifying velocities according to the points of the compass. The number of storms used varied according to the latitude of the station, northern stations having a greater number than southern.

THE GULF COAST.

On the east Gulf coast.—Storm warnings are not often required on the Florida coast south of Tampa, and very nearly all of them are northeast warnings necessitated by the approach of tropical storms. As on the Atlantic coast, these warnings should be ordered, if possible, 24 hours before the storm reaches any given locality, and the hurricane warnings, of course, should replace the storm warnings as soon as the approach of a violent storm is indicated. Rarely southwest warnings may be needed on the southern coast, if a storm passes eastward over the Gulf of Mexico with its center a few hundred miles south of the middle coast. This, however, is a very unusual condition and one that need not be elaborated. From Tampa northward to Cedar Keys southwest warnings are indicated when a storm passes through the southern portion of the Gulf States or the northern portion of the Gulf of Mexico, and a change to northwest will usually be necessary before the wind finally diminishes. Northeast warnings are of course needed for tropical storms, just as at other points in the Florida Peninsula. From Cedar Keys westward storm displays are of more frequent occurrence and they are usually southerly warnings, necessitated by LOWS passing northeastward through the Gulf States, and a change to northwest will also be necessary as the LOW passes. At times it will first be necessary to order southeast warnings when

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the storm center is some distance to the northwestward, but as a rule, the southeast wind is not of long duration nor as strong as those from the southwest. An exception should be noted for the stretch of Gulf coast between Carrabelle and Pensacola, Fla. Here the southeast winds blow from the open Gulf with great velocity—much higher than indicated by the barometric gradient—and these southeast winds are frequently persistent for a considerable time, while no high winds are blowing either to the eastward or to the westward so far as station reports indicate.

Northeast warnings are advisable whenever a LOW is moving across the Gulf from the west or whenever a tropical disturbance has entered the Gulf and has recurved over the middle Gulf. Should a tropical storm move northwestward and recurve over the Florida Peninsula, or a short distance to the westward, northwest warnings would be needed from the mouth of the Apalachicola River westward.

The LOWS that reach Texas and then move northeastward will usually cause strong winds on the Gulf coast, and they frequently call for display of small craft warnings from Mobile Bay eastward to Cedar Keys, and rather less frequently for southeast storm warnings from Pensacola to Carrabelle. It appears that whenever the barometer over Texas reads about 29.75 inches, with a pressure of about 30.30 inches over Florida, small-craft warnings will be needed on the east Gulf coast and, if the storm does not turn too sharply to the northeastward, southeast and southwest storm warnings will also be needed north and west of Tampa.

On the west Gulf coast.—Storm warnings on the Louisiana coast are not frequently needed, and those ordered are usually for southeast and southwest winds with a later shift to northwest. They are necessary whenever LOWS of well-defined character move northeastward across central or southern Texas, and the velocity of the wind will increase as the paths of the storm centers incline southward toward the Gulf. Northeast warnings are indicated, though rarely, with storms coming up from Mexico or the extreme southwest, via the mouth of the Rio Grande and the west Gulf of Mexico. Such disturbances are apt to increase in intensity as they move northeastward, but it is safe to order the warnings just before the storm leaves the mouth of the Rio Grande. Should there be a pronounced high not very far to the eastward and northeastward and the low center be well defined, the winds will increase about as soon as the low center leaves the Gulf coast, and northeast warnings should be ordered shortly before that time, changing later to northwest as the storm center passes. Should a tropical disturbance move across the Gulf near or close to the Texas coast, as sometimes occurs, and then recurve, northeast warnings will also be required with a change to northwest as the storm center passes. If the storm should recurve

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far to the southward and then increase in energy, it might be necessary to order hurricane warnings for the Louisiana coast, and even to the Texas coast at times. Winds on the Texas coast appear to be much stronger than on the Louisiana coast and blow mainly from the southeast and south. Here warnings are needed quite frequently, at least small-craft warnings, and whenever a strong HIGH with a decided drop in temperature follows a LOW through Texas, there will be a shift of winds to the northward with a decided increase in velocity, very often reaching the proportions of a moderate gale. It is important to forecast these northwest gales for Galveston particularly, as at that point north winds drive water from the bar and prevent deep-draft boats from entering the harbor.

STORM WINDS ALONG THE GULF COAST.

Percentage of storm winds from the north, northeast, etc., for each station of the Gulf coast, 1905 to 1914, inclusive, and verifying velocities in miles per hour.[1]

Stations.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Verifying velocity.
Key West, Fla	5	4	2	5	9	14	22	39	32
Tampa, Fla	3	12	15	10	9	26	12	12	28
Pensacola, Fla	8	5	11	21	18	17	4	17	40
Mobile, Ala	11	3	11	18	7	13	7	31	38
New Orleans, La	19	12	1	25	19	7	4	14	30
Galveston, Tex	24	10	8	11	3	1	5	38	32
Corpus Christi, Tex	18	8	16	42	9	0	0	8	38

[1] The highest verifying velocity for each storm was tabulated for the period of 10 years for each of the 8 principal points of the compass, 1 entry only being made for each storm that gave a verifying velocity. The table shows, therefore, the ditribution of verifying velocities according to the points of the compass. The number of storms used varied according to the latitude of the station, northern stations having a greater number than southern.

STORM WINDS ON THE GREAT LAKES.

Lake Superior.—The most important storm warnings that are displayed on Lake Superior are those for northeast winds, which generally back later to northwest, as most of the LOWS causing high winds over Lake Superior pass to the southward of the lake. Sometimes LOWS move eastward over the Canadian Northwest and over Lake Superior; these LOWS call for southeast warnings changing to northwest as the center passes. Occasionally when the barometric gradient is very steep it may be advisable to begin with a southeast warning, changing to southwest as the center approaches and changing to the northwest as it passes. Probably the most severe of these storms are those that move southeastward over the Plateau region or along the eastern slope of the Rocky Mountains and then turn to the northeastward after reaching Nebraska or Kansas. These almost invariably increase in intensity as soon as they turn to the northeast-

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ward; and, should there be moderate HIGH over the extreme north, very severe northeast gales with heavy snows will occur from late autumn until late spring. Care should be taken not to order too many warnings, but no chances should be taken whenever increasing northeast winds are indicated. It should be remembered, however, that it is not essential for a LOW from the southwest to have a marked HIGH in front of it. The natural increase in the LOW will serve to build a relative HIGH to the northeastward and cause high winds, provided there is some rising pressure with falling temperature to the westward and southwestward. Should this condition be lacking to the westward, it is not probable that there will be any severe east to north gales on Lake Superior, notwithstanding the fact that the barometer may be quite high to the northward and eastward; and it appears to be an essential condition, as said before, that there should be rising pressure and lower temperature in the rear of the storm. The map of April 24–25, 1914, will illustrate this point.

Southeast to southwest winds are the least dangerous on Lake Superior; and in cases of doubt as to whether or not the winds will be strong, the small-craft warnings will usually answer every purpose for southeast to southwest winds, unless snow is expected, in which case it is better to order storm warnings, even though the forecaster does not think that the verifying velocity will be reached. Navigation in a snowstorm is the most difficult work that a vessel master is called upon to perform, and the knowledge that the winds will increase, even though they do not become high, will be of the greatest value to him. Of course, with a northeast storm, no chances can be taken, especially if snow is indicated, as a northeast wind of even 25 to 30 miles an hour blowing steadily for half a day will create a high sea, which will be continued when the winds back to northwest; whereas south to southwest winds of even 40 miles an hour will not make much trouble unless accompanied by snow.

Lake Michigan.—It often appears that a LOW moving directly across Lake Michigan necessitates northerly warnings for the north portion and southerly warnings for the southern, both being combined in a northwest warning as the storm passes. It also happens at times that a northeast warning will be indicated for Lake Michigan and not for Lake Superior or for southern Lake Michigan and not for northern Lake Michigan. These cases arise when a marked disturbance is passing across the Central Valley from the southwest, when the first warnings will be northeast and afterwards northwest. On the west shore of Lake Michigan heavy southwest winds are not usually dangerous, except in Green Bay, and small-craft warnings will answer for any winds short of a fresh gale, provided no snow accompanies the wind. On the east shore, however, westerly winds naturally create a heavy sea, and the southwest and northwest warn-

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ings are of more importance than the northeast warnings, so far as the immediate vicinity is concerned. Of course, as the lake is narrow, information regarding northeast winds is just as important as on Lake Superior or western Lake Michigan, because when a boat leaves the east shore bound west or northward it will not be long before it will come under the influence of the northeast wind should such be blowing. Naturally every precaution should be taken when snow is indicated.

Lake Huron.—The remarks regarding Lake Michigan apply with almost equal force to Lake Huron.

Lower Lakes.—Storm warnings on the Lower Lakes usually begin either with northeast or southwest warnings; if the latter, they will, in most cases, be followed by a change to northwest as the storm center passes. Northerly warnings, whether northeast or northwest, are perhaps the most important on these lakes. Northeast warnings are indicated with the approach of LOWS from the southwest, and, if there is a fair gradient to the northward, they should be ordered about the time the storm center reaches the lower Ohio Valley, Occasionally LOWS come up from the south, moving northeastward from the west Gulf States. These also call for northeast warnings on the Lower Lakes, and they should be ordered about the time the LOW covers the northern portion of the east Gulf States. Very rarely a LOW moving up from the South Atlantic States will back in sufficiently to necessitate northeast warnings for Lake Ontario. Southwest warnings are perhaps more frequent than any other on the Lower Lakes, and they are indicated by the passage of the numerous LOWS from west to east over the northern portion of the country. It may occasionally be necessary to begin with a southeast warning when the storm center is around the upper Mississippi Valley, but in such cases the message should also contain the information that the wind will change to the southwest and should give the time if possible. The highest velocities will be found to occur with the southwest storms, particularly over Lake Erie. Before the storm center passes warnings will usually be changed to northwest, from which direction the wind will blow with undiminished velocity for some time after the LOW passes, particularly if there has been a decided fall in temperature accompanying the western HIGH.

Here again it must be noted that unless there is a strong rising pressure to the immediate westward with lower temperatures, very high velocities will not be reached, even though the gradient may be steep with a fair HIGH in front of the LOW. Of course, as on the Upper Lakes, it will be advisable, if the winds are blowing from the northeast with or without snow, but especially with snow, to take no chances. As southwest warnings in most cases are much less dangerous, small-craft warnings will frequently serve unless snow

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is indicated; but if there is a fair gradient to the west, it is always advisable to hoist the warning indicated. High winds on the Lower Lakes are more frequent than on the Upper, due most likely to the fact that most of the LOWS either from the Northwest, Southwest, or Central West, move northeastward by way of the Lower Lake region and the St. Lawrence Valley.

See the table of storm winds on the Great Lakes, page 252.

THE NORTH PACIFIC COAST.

By E. A. BEALS, District Forecaster.

As practically all the storms affecting the North Pacific States come from the Pacific Ocean, where there are no weather stations, the first intimation of an approaching storm is indicated by the two-hour pressure changes at Tatoosh Island, North Head, Marshfield, and Eureka. During the last three years valuable information has been obtained from the Alaskan stations.

If the two-hour pressure changes from Tatoosh Island, North Head, Marshfield, and Eureka show the greatest fall at Tatoosh Island and a slightly less fall at North Head, no change at Marshfield and a slight rise at Eureka, the center of the depression is either in the Alaskan Bight of the Pacific Ocean or over the western portion of British Columbia.

If the two-hour fall is greatest at North Head, the storm is off the Washington coast, and if the two-hour fall is greatest in the south and least in the north, the depression is off the southern Oregon coast.

Another guide to the location of the depression is the direction of the wind at the foregoing stations, which is indicated according to the well-known law of storms, whereby inflowing winds in the Northern Hemisphere move counterclockwise.

The intensity of the LOW is noted by the amplitude of the two-hour pressure changes. If the fall equals or exceeds 0.06 inch at one station and the one farthest from it shows a small rise, the depression is either of no great magnitude or else only a portion of the depression will affect the North Pacific States.

The foregoing condition, however, indicates the gradients are growing steeper, and warnings should be issued at once. If all stations show a marked fall, the depression is of great magnitude and should be treated accordingly.

Besides the two-hour pressure changes, an excellent guide to the nearness of an approaching storm is obtained from the movement of the lower clouds at the coast stations. When they are moving rapidly from the east, southeast, or south warnings should be issued at stations in the neighborhood at once, provided the two-hour barometer changes are at all favorable for a storm.

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The adjacent pressure distribution is the all-important fact in determining the path of a LOW. If the HIGH is over the Plateau States and the barometer is relatively low over the Canadian Northwest a rapid movement will take place and the storm will be of short duration. If the HIGH is over Alberta and Montana the progress eastward of the depression will be blocked and the storm will be of long duration.

In November, December, January, and February LOWS follow one another in rapid succession. There are generally three in a group, with not more than an interval of a day, or at most two days, between them. They appear to be offshoots of a very deep and large LOW over Bering Sea, which, instead of moving intact, disintegrates in sections. Therefore, with rising barometer along the North Pacific coast and every condition indicating that a first storm is over, it should be borne in mind that another, of equal if not greater severity, is probably near the coast, and extreme caution must be exercised in notifying shipping that it is safe to leave port.

Nearly all warning on the North Pacific coast are for either southeast or southwest winds. To determine whether the warning should be for southeast or southwest winds the cloud movements are of great help, as the direction of the lower clouds is generally 4 points or more to the right of the surface wind, and if the clouds are coming from the south it is better to order southwest rather than southeast warnings, even if the surface wind is from the southeast, as it will shift to the south in an hour or two provided the LOW is advancing at an average rate of speed; otherwise southeast warnings should be ordered.

Northeast storm winds occur with a HIGH over British Columbia and a LOW off the Oregon coast. Should the pressure chart show such a distribution, with a deepening of the LOW and a building up of the HIGH likely to cause gradients, say, of seven or eight tenths of an inch from Kamloops to Marshfield, northeast warnings should be ordered. These winds are especially dangerous in the harbors along the Strait of Fuca, and, as they are always attended by cold weather and generally by snow, it is not necessary for the winds to become very high to be hazardous; therefore the warnings for these winds should contain information regarding low temperatures, and snow if the latter is expected.

The movement of a typical winter storm in this district is illustrated by figures 159–162. There was nothing to indicate the approach of this storm on the morning chart of November 28, 1913. The general pressure conditions, while not alarming, were disquieting, and the forecaster thought it best to call for a few special observations. The last of these was received shortly before noon, and showed the barometer to be falling rapidly and the winds slowly

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increasing. Storm warnings were accordingly sent to all stations as soon as possible. By the evening (see fig. 160) the storm had reached the coast stations at North Head, Wash., 68 miles southeast, and at Tatoosh Island, Wash., the maximum velocity during the same period was 52 miles east.

Rarely is it possible to forecast high northwest winds along the north Pacific coast, and rarely do they occur. They are caused by a LOW over Oregon and a HIGH at sea north of the mouth of the Columbia River. Usually in the winter, when the barometer rises rapidly at coast stations, it stops rising in the north within a few hours, and the fact of a rapid rise does not denote the presence of a large HIGH in a region where they so seldom occur, while a rapid fall in pressure is a sure indication of an approaching LOW.

The verifying velocity for southeast winds at coast stations is 60 miles an hour and for southwest winds 48 miles an hour. When a velocity of 35 miles southeast or 25 miles southwest is reported, and the clouds and the two-hour pressure changes are disquieting, special observations should be called for.

In conclusion, it is proper to state that storm warnings on the north Pacific coast can seldom be displayed more than from 4 to 12 hours in advance of the attainment of a verifying velocity, but in the Puget Sound country they are nearly always ordered 12 hours ahead of the disturbance, and sometimes a full day ahead of the danger period.

See the table on page 248.

THE SOUTH PACIFIC COAST.

By GEO. H. WILLSON, District Forecaster.

In forecasting high winds the value of the warnings depends upon their dissemination sufficiently in advance of the occurrence of the dangerous velocities to enable those interested to make the necessary preparations to protect themselves and their property.

There are two prime factors to be considered in connection with high winds in this district: (*a*) HIGHS of great magnitude moving southward over British Columbia, the Pacific States, and the Plateau region, and (*b*) LOWS moving inland from the Pacific Ocean.

When an area of abnormally high pressure moves southward over British Columbia, the Pacific States, and Plateau region, a steep gradient is formed to the south and southwest, causing high north to east winds along the coast. These conditions are not difficult to forecast, as the crest and the position of the HIGH are clearly indicated on the charts, and the barometric changes along the coast and for some distance inland are quite regular. The steepness of the gradient is apparent, and the velocities of the wind along the coast are not

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difficult to anticipate, as the entire pressure condition is generally one of steady and uniform movement.

The LOWS causing high winds along this coast come directly from the ocean, and their extent and depth are unknown until after they have passed inland, and the dangerous southeast to southwest winds have greatly diminished and shifted to the west and northwest. It is, therefore, necessary that the forecaster detect the first intimation of the approach of a LOW from the ocean, and then approximate the direction and movement, extent and probable duration of the storm and the direction and velocity of the wind and issue the necessary warnings. One can not wait until the wind has begun to increase and show indications of reaching a high velocity.

It would be next to impossible to lay down any fixed rules for interpreting the wind velocities on the approach of a storm along this coast. A rapid fall in pressure at any of the coast stations, accompanied by a shifting of the winds to the south or southeast, with increasing cloudiness, is nearly always a sure sign of the approach of a "southeaster," the most dangerous storm on this coast. It is seldom that a forecaster can wait for all of these, as most storms of this character move in very rapidly from the ocean, and a high wind precedes or accompanies some of these manifestations. If a HIGH appears over British Columbia or Alberta, or the pressure is much above the normal in those Provinces, when the barometer begins to fall rapidly along the coast, and the wind shifts to south or southeast, the approaching LOW will be deflected southward, and high southeast winds will occur within a few hours. Under these conditions a minus 12-hour change in pressure along the coast, if supplemented by a fall of 0.04 inch, or more in two hours, at Eureka or North Head and a shifting of the wind to a southerly direction on Mount Tamalpais, is generally sufficient data on which to base a southeast warning. When the pressure is comparatively low and falling over British Columbia, and a LOW is approaching the coast of Oregon or Washington, and the wind on Mount Tamalpais continues fresh or brisk from the west or northwest, high southeast wind will not occur south of Cape Mendocino and the LOW will move eastward at a high latitude, following the normal storm track. The extent of the high wind southward can best be determined by the height of the barometer at San Francisco or San Luis Obispo and the gradient northward as shown by the reports.

In addition to the above, the writer follows closely and is guided by the pressure-change chart, especially the 12-hour changes as indicating the intensity of a LOW and its direction and rate of movement. When the conditions are well defined and the changes rapid it is well to be on the alert for the approach of a LOW as soon as the north and south axis of the HIGH has passed inland. This is very im-

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portant, when there is a large difference between the 24 and 12 hour changes in pressure along the coast.

It is not safe to discontinue a storm warning while the wind continues from the southeast or east at coast stations north of San Francisco, and the pressure continues high over British Columbia, even though the pressure begins to rise along the coast. Under these conditions the storm has only shifted back over the ocean and will return within 36 hours or less.

Of course, the forecaster must always use his good judgment in ordering storm warnings, sometimes slight changes indicate the approach of the storm and at other times nearly all early indications fail, and it is at these times that careful discrimination is necessary.

STORM WINDS ALONG THE PACIFIC COAST.

Percentage of storm winds from the N.; NE., etc.; for each station on the Pacific coast, 1905 to 1914, inclusive, with verifying velocities in miles per hour.[1]

Stations.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Verifying velocity.
Tacoma, Wash.	3	9	4	0	1	78	6	0	26
Seattle, Wash.	1	0	0	2	45	48	2	3	35
Port Crescent, Wash.	0	50	2	0	17	31	0	0	25
Tatoosh Island, Wash.	0	7	23	8	44	16	6	2	[2] 48
North Head, Wash.	0	0	0	54	30	2	2	12	[3] 48
Eureka, Cal.	50	0	0	17	5	17	2	10	36
Point Reyes Light, Cal.	5	1	1	2	21	4	0	66	40
San Francisco, Cal.	0	27	0	6	8	56	9	0	36
Los Angeles, Cal.	2	6	0	16	15	49	1	12	[3] 30
San Diego, Cal.	4	0	0	14	39	18	25	0	30

[1] The highest verifying velocity for each storm was tabulated for the period of 10 years for each of the eight principal points of the compass; one entry only being made for each storm that gave a verifying velocity. The table shows therefore the distribution of verifying velocities according to the points of the compass. The number of storms used varied according to the latitude of the station, northern stations having a greater number than southern.

[2] 60 miles from southeast.

[3] Except 20 miles between southeast and southwest.

STORM WINDS ON THE UPPER GREAT LAKES.

By H. J. Cox, Professor of Meteorology.

Lows approaching the Lakes with a decreasing pressure will cause increasing winds over the Lake region, and ordinarily a gale is probable if the pressure is likely to fall as low as 29.50 inches. The force of the wind, however, will depend upon the barometric gradient surrounding the LOW rather than the actual pressure in the LOW itself.

A type of the most severe storms on the Upper Lakes is shown by the weather map of February 8, 9, and 10, 1894, when a well-defined LOW moved from the west Gulf region directly northeastward over the Lakes, while at the same time a cold HIGH of great magnitude

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appeared in the British Northwest. The highest velocity ever recorded at Chicago was reached on this date, 84 miles an hour from the northeast. When a LOW is centered over the west Gulf region and in its movement northeastward the center passes directly over the heart of the Lakes, general gales are likely to result over the entire section. If the southern LOW is as far east as New Orleans and it moves northeastward, it will affect only the Lower Lakes and the southern portion of the Upper Lakes.

When a LOW is centered in the upper Mississippi Valley, over Minnesota, for instance, and a HIGH is crowding down from Manitoba with the isobars north of the LOW running in an east-west or northeast-southwest direction, the gale on the Lakes promises to be exceptionally severe, especially if the LOW is deep and the gradient to the north steep. The maps of May 17–18, 1894, represent a good type of this condition. In this case, of course, the pressure was falling over Lake Michigan and rising over Manitoba. The LOW was centered on the 17th over Minnesota and on the 18th over the Lower Lake region. This storm caused greater destruction to shipping on Lake Michigan than probably any other storm in the history of the Weather Bureau, a large number of vessels being wrecked at the southern end of the lake. The maximum wind velocity at Chicago was 62 miles an hour and the direction of the gale from northeast to north. In the month of May storms usually lose force as they approach the Lakes, but in this instance the LOW deepened.

A modification of the above type is that of October 25–26, 1898. In this case the LOW was centered over northern Illinois with the isobars to the north running from northeast to southwest, but the following HIGH, instead of being in the British Northwest, was central over the middle Rocky Mountain region. The maximum wind velocity at Chicago during this storm was 47 miles.

The maps of February 19–20, 1898, represented a type with the isobars running east-west over the Lakes. The gale was not high according to actual wind velocities, the maximum at Chicago being 45 miles from the east, but, nevertheless, the storm was severe and quite damaging to vessel interests that maintained shipping during the winter season. Storms of this character are especially dangerous because of the attendant snows which continue for some time after the center of the disturbance passes eastward.

The reported wind velocities do not always indicate the severity of a storm because of the fact that exposures of the instruments do not permit high velocities from some directions at certain stations. The map of April 28, 1914, is an illustration of such a condition, no maximum wind velocities being reported from Houghton or Marquette, although the barometric gradient was strong in the vicinity

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of these two stations, and at the same time maximum velocities were reported from Duluth and Sault Ste. Marie.

When a LOW approaches the Lake region attended by a pressure fall of 0.40 or 0.50 inch in its front, severe gales may be expected on the Lakes, and if the LOW is deepening the storm is likely to be exceptionally severe. These storms are particularly damaging when they approach the southern Lake region from the State of Iowa in the autumn and winter. (Jan. 20–21, 1895; Jan. 28–29, 1909; Dec. 5–6, 1906; Jan. 19–20, 1907; Feb. 5–6, 1908; Mar. 13–14, 1913; Jan. 2–4, 1906; and Jan. 25, 1895.)

As LOWS approach the Great Lakes region during the spring and early summer, they are likely to lose energy because of the chilling influence of the Lakes, while in the autumn and winter they increase in energy.

A storm warning should rarely be issued for Lake Michigan when the storm center has approached no nearer than Kansas unless the storm promises to be of exceptional severity, with very rapid movement. If warnings are issued so far in advance of a storm center, great injury is often done to shipping intrests, as the storm may lose in energy in its movement eastward or northeastward, especially in the spring of the year.

No warnings should be issued for the Lakes longer than 12 hours in advance of storm velocities, as the runs of vessels are often from port to port. Moreover, when the run is for the full length of any lake, the display of warnings may be seen at storm-warning stations in the fairway and harbors of refuge are close at hand. It should be realized that when storm flags are hoisted it is an indication that danger to navigation is imminent. No absolute rule can be given which will cover all storms, but each one should receive special and individual treatment.

A storm moving eastward over the southern Lake region is usually far more dangerous and severe and more extensive than one whose center passes eastward over Lake Superior, as the full force of the gale is felt at the various stations from several points of the compass.

When a storm is moving eastward or northeastward over the Great Lakes attended by gales, a decrease in wind may be expected just as soon as the pressure in the center of the disturbance begins to increase. (Oct. 17 and 23, 1898.)

When the barometer rises rapidly during a gale on the Lakes after the center of the LOW has passed the wind may be expected to rapidly decrease in force.

In the fall or spring, particularly in the latter season, when the pressure is low to the south of the Lakes and a HIGH covers the upper Mississippi Valley, dangerous northerly gales will ensue in the southern Lake region. (Apr. 15, 1908; Mar. 30–31, 1906.)

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Sometimes a high crowding southward from the northern Lake region or the upper Mississippi Valley with steep gradient will cause high northerly winds without any accompanying depression to the south or southeast. (Nov. 28, 1898; Feb. 13, 1906; Jan. 20–21, 1910.)

Storm conditions are most pronounced on the Great Lakes when the LOW is followed by a well-marked HIGH in the northwest. If no HIGH of consequence follows the storm, the development of the LOW itself is alone responsible for any gales resulting. (Feb. 13–14, 1907; Jan. 26, 1908.) If a HIGH with a strong gradient follows in the rear, the gale will continue when the wind shifts to the northwest. (Dec. 6–7, 1913; Oct. 26–27, 1906.)

A LOW moving from the southwest, northeastward over the Ohio Valley, will never cause a gale on Lake Superior and ordinarily only over the southern end of Lake Michigan.

The thermal gradient as well as the barometric gradient must be considered in ordering storm warnings, and if considerable rise in temperature is anticipated with southerly breezes, the wind will increase decidedly in velocity; rapidly falling temperature will also affect the velocity of the wind.

During the warm season of the year high velocities are seldom attained on the Lakes, except during thunderstorm conditions, and these are usually so local that advisory or small-craft warnings are sufficient.

Gales accompanied by snow are very dangerous, because during such conditions the master is often unable to properly navigate his ship.

On-shore gales are dangerous, while those blowing off-shore cause but little damage and forecasters should take this fact into consideration in issuing storm warnings.

In ordering storm warnings a forecaster should think of the effect and strength of the winds on the open lake and this is shown approximately by the barometric gradient. Even with the same gradient, the recorded wind velocities at some stations differ widely from those at others, simply because there is such a great difference in the exposure of the anemometers and the configuration of the country adjacent to and surrounding the Weather Bureau observatories. There is no difference in topography, however, on the open lake. In the storm of April 27–28, 1914, when high wind velocities were recorded at Duluth but none of consequence at the other Lake Superior stations, although the barometric gradient was steep over the entire lake, the gale was certainly as severe in the eastern and central portions of the lake as in the western portion. On page 157, Weather Bureau Bulletin No. 24, Report of the Omaha Convention, I showed that of all the recorded storm velocities during a period of five years at Marquette, Mich., there was none from the northeast

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or east and only 4 per cent from the north; at Sault Ste. Marie there was none from the north, only 3 per cent from the northeast, and 2 per cent from the east; while at Duluth there was 1 per cent from the north, 30 per cent from the northeast, and none from the east. These remarkable difference are due to local peculiarities of exposure of the anemometers, rather than to variations in wind force on the open lakes.

STORM WINDS ALONG THE GREAT LAKES.

Percentage of storm winds from the north, northeast, etc., for each station on the Great Lakes, 1905 to 1914, inclusive, and verifying velocities in miles per hour.[1]

Stations.	N.	NE.	E.	SE.	S.	SW.	W.	NW.	Verifying velocity.
Duluth, Minn	1	19	0	0	0	13	20	46	46
Houghton, Mich	18	5	7	4	0	0	40	26	24
Marquette, Mich	0	1	4	4	21	36	13	21	32
Sault Ste. Marie, Mich	1	2	2	2	0	4	38	50	30
Escanaba, Mich	24	21	6	2	6	9	6	25	28
Green Bay, Wis	28	15	0	2	5	14	26	8	36
Milwaukee, Wis	7	16	21	18	3	25	5	5	36
Chicago, Ill	5	12	2	2	8	27	34	10	36
Grand Haven, Mich	3	0	0	1	10	26	42	17	36
Alpena, Mich	0	4	12	18	14	14	13	25	36
Port Huron, Mich	9	4	2	4	2	12	30	35	32
Detroit, Mich	5	3	4	0	3	25	41	18	40
Cleveland, Ohio	8	2	0	11	11	17	34	17	40
Buffalo, N. Y	0	0	0	0	2	62	32	4	54

[1] The highest verifying velocity for each storm was tabulated for the period of 10 years for each of eight principal points of the compass; one entry only being made for each storm that gave a verifying velocity. The table shows therefore the distribution of verifying velocities according to the points of the compass. The number of storms used varied according to the latitude of the station, northern stations having a greater number than southern.

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Chapter IX.

HEAVY SNOW, SLEET, AND ICE STORMS, FOG.

By Prof. H. C. Frankenfield.

THUNDERSTORMS.

By Prof. A. J. Henry.

Heavy snow:
- Foreword 253
- Distribution, seasonal and geographic 254
- Meteorological conditions preceding 254
- Sleet or heavy snow—which? ... 256

Fog:
- Foreword 260
- Lake region fogs 261
- Seasonal distribution 261
  - Upper Great Lakes 261
  - Conditions favorable for formation of 261
  - Lower Great Lakes 263
- General remarks 263
- Atlantic coast fog 264
  - Geographic distribution of .. 266
  - Seasonal distribution of 266
  - Necessary conditions precedent to formation of 268
- Gulf of Mexico fog 269
  - General remarks 272

Fog—Continued.
- Pacific coast 273
  - Washington and Oregon 273
  - Northern California 273
  - Southern California 274

Sleet and ice storms:
- Definitions 257
- Geographic distribution of 258
- Seasonal distribution of 259
- Conditions favorable for 259
- Conclusions 260

Thunderstorms:
- General statement 274
- Geographic distribution 275
- Seasonable distribution 275
- Diurnal variation 275
- Relation to pressure distribution. 275
- With indefinite pressure distribution 276
- Connection with Atlantic highs. 277
- Generated by excessive temperature and high humidity 277
- Winter thunderstorms 278
- Recapitulation 278

HEAVY SNOW.

Foreword.—The paper by the late Prof. E. B. Garriott on heavy snowfalls in the United States, published in "Studies of Weather Types and Storms" (Weather Bureau, No. 92, 1896), contains an exhaustive presentation of the subject, and the present discussion, in so far as the snowfall itself is concerned, will be in the main a summary of Prof. Garriott's paper, with, however, a few additional suggestions that later experiences have dictated.

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Distribution, seasonal and geographic.—Naturally, the majority of heavy snowstorms occur in January and February, especially in January. Quite a number also occur in December and March, and a lesser number in November. There were none of consequence observed in any other month.

Heavy snows are most frequent in New England and the Middle Atlantic States, the Great Lakes region, the Ohio and upper Mississippi Valleys. They occur less frequently in the Missouri Valley, central Rocky Mountain region and the Northwest, and very rarely in Tennessee and the north portions of the Gulf and South Atlantic States. The regions of maximum frequency are the New England and the Middle Atlantic States, particularly the north portion of the last-named district.

Meteorological conditions preceding heavy snows.—Heavy snows are caused by the eastward movement of well-marked LOWS, accompanied by cold and equally well-marked HIGHS, to the northward. This is the best type, although heavy snows occur quite often when the HIGH to the northward is not very well marked, but is comparatively cold. It is true that at times the same type of pressure distribution causes sleet instead of snow, but in such cases other contributory causes are different. This subject will be discussed later.

Lows from the northwest that are attended by heavy snows are comparatively warm; they usually move southeastward along the eastern slope of the Rocky Mountains and are closely followed by rapidly rising pressure from the northward or northeastward, with temperatures below the freezing point. These LOWS usually turn to the eastward and northeastward after reaching South Dakota or Nebraska, and the latter State will usually mark the southern limit of heavy snowfall. Occasionally, however, the LOW will continue southward as far as Oklahoma or Texas, and in such cases heavy snow will fall in eastern Colorado, Kansas, and, at times, in Oklahoma and North Texas. Should the HIGH to the northward—*not* to the northeastward—be very cold and the barometric gradient very steep, there will result the combination of heavy snow, low temperatures, and high northerly winds, known as a "blizzard," and in Texas as a "norther," although the "norther" is not necessarily accompanied by snow.

The heavy snows of the central Rocky Mountain region are usually preceded by LOWS moving eastward from the southern plateau, regardless of their origin, with a HIGH to the northeastward that need not necessarily be a well-marked one, provided the temperatures 24 to 36 hours later will be below the freezing point. If the LOW keeps well to the southward and there is sufficient cold to the northward, the heavy snow will extend well down toward the storm center. This is the true type of pressure distribution for heavy snow,

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observed at its best in New England and the Middle Atlantic States, and consists essentially of a southern LOW moving eastward or northeastward (see fig. No. 163), attended by temperatures below freezing north of the storm center. The type is so well defined and the departures therefrom are so rare and comparatively unimportant that detailed discussion appears to be unnecessary. (See also weather maps of Feb. 13, 1899, Jan. 27, 1912, and Feb. 16, 1910.)

But a single instance of a radical departure from the type was encountered, namely, that of February 5–6, 1908, when a western LOW moving east-northeastward over the Upper Great Lakes was attended by east to south winds and heavy snows over the District of Columbia, Maryland, Delaware, and the southern portion of New Jersey and eastern Pennsylvania. In this case temperatures were generally low and there was a well-defined HIGH to the northeastward that caused strong northeast and east winds and heavy snows over the districts to the north, constituting the regular type for that section.

Occasionally there will be heavy snowfall with the HIGH to the northwest, as on January 16, 1915, over eastern and southern Minnesota, western Iowa, and eastern Nebraska. A well-defined LOW from the extreme southwest turned north-northeastward after reaching central Texas, and on the morning of January 16 was over western Missouri (29.50 inches), with a moderately cold HIGH (30.42 inches) over eastern Montana. Heavy snow fell during the day, as above noted. Another type of snow over the northern Rocky Mountain region is shown in figures 164–166. Note especially the development of a secondary over Texas on February 16, 1910, and the resulting snow along the margin of the cold northerly winds.

SUMMARY.

1. In general heavy snow falls to the north of the path of the center of the LOW and south of the center of the HIGH to the northward.

2. Snow will begin with northeast to east winds, usually northeast, and cease, as a rule, soon after the wind shifts to southwest and northwest.

3. Snows will begin almost as soon as the wind shifts to northeast or east, provided the wind is blowing with at least a gentle to moderate velocity (12 to 25 miles per hour), without regard to the height of the barometer in the HIGH.

4. Other conditions being favorable, snowfall will probably be heaviest when temperatures are between 24° and 30°. However, an occasional marked exception to this rule occurs. (See Feb. 11 and 12, 1899; Middle Atlantic States and New England.)

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5. When heavy snow in the central and eastern districts is caused by LOWS from the west and northwest the storm center passes south of the region of heavy snowfall; snow usually begins when the storm center is to the southwest of the section, continues during the passage of the center to the southward, and until it has passed well to the eastward (Garriott).

6. Heavy snows in the Rocky Mountain districts are sometimes caused by the development of secondary LOWS over the middle Rocky Mountain district, with a HIGH to the northward.

SLEET OR HEAVY SNOW, WHICH?

As the pressure distribution necessary for sleet and heavy snow is much the same, it is obvious that, if this alone were considered,

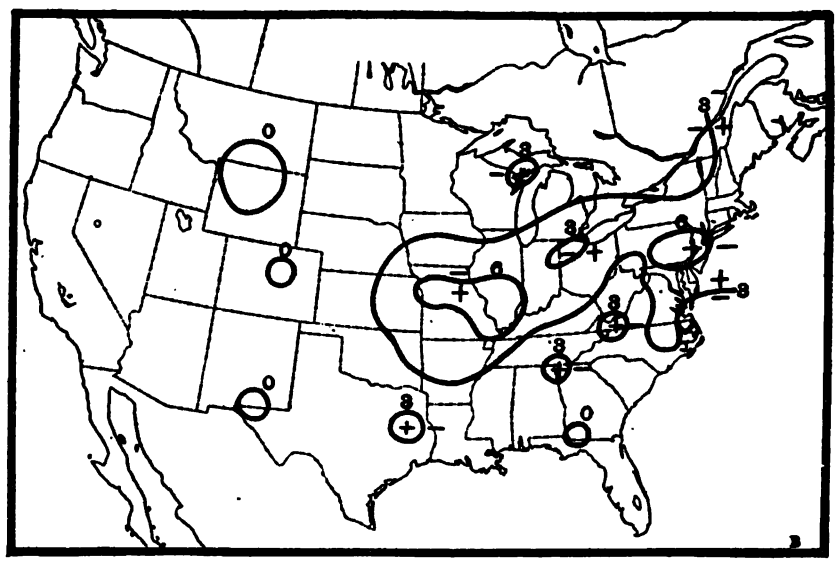

FIG. 167.—Annual frequency of sleet storms.

many forecasts of heavy snow must fail of verification because sleet would occur instead of heavy snow.

Study of the question has developed that (1) the steep temperature gradients to the northward of the storm center usually preceding sleet formation are not necessarily present in advance of heavy snowfall, and, (2) what is a much more important and probably the essential point of difference, the high temperatures over the Gulf and South Atlantic States that appear to be essential to sleet formation to the northward are absent before and during heavy snows. A third and also important point of difference is that the high temperatures over the Gulf and South Atlantic States that precede sleet are accompanied by southeasterly to southerly winds, which, coming

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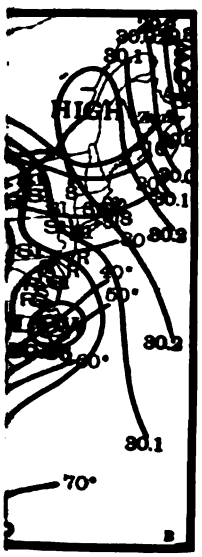

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from the warm water surfaces, carry a much larger water content than winds from any other direction.

Out of 48 cases of heavy snows, 28 were preceded by cool weather over the South and only 5 by warm weather. Five others were preceded by warm winds but with cool weather closely following. About a dozen others were preceded by warm winds but were from southwest to north and northeast, away from the sources of excessive moisture supply.

Out of 34 cases of sleet, 29 were preceded by warm southerly winds over the South Atlantic and Gulf States, indicating an excessive moisture supply. Figure 168 illustrates a sleet type for the Middle Atlantic States. Figures 169 and 170 illustrate a type for the interior valleys, and the weather maps of February 13–14, 1909, not reproduced, illustrate a lake-region type.

General rule.—Whenever either sleet or heavy snow is indicated, forecast sleet when warm southerly winds prevail over the South Atlantic and Gulf States and heavy snow when they do not. This rule, however, does not apply to forecasts for the Northwestern States.

SLEET AND ICE STORMS.

Definition of terms.—The term "sleet" has been variously defined and some of the definitions are manifestly inconsistent. The definition adopted by the Weather Bureau appears to be rational and consistent, and is as follows:

Sleet is precipitation that occurs in the form of frozen or *partly frozen* rain, and is formed by rain falling from a relatively warm air stratum into and through another air stratum that is sufficiently cold to freeze some or all of the rain drops. Mixtures of snow and rain are distinctly not sleet; neither are mixtures of hail and rain, as some of the foreign definitions permit.

Another related phenomenon is the English "glazed frost," the German "glatteis," the French "verglas." This is rain that falls to the surface as rain but freezes as soon as it touches the surface.

It is most manifest on telegraph and telephone wires, trees, etc., and is the form that causes the greatest damage. The true sleet, falling as mingled ice and rain, does not cling and does not often cause much damage. Both forms, however, are preceded by the same general meteorological conditions.

The etymology of the term "sleet" is uncertain and none of the earlier available equivalents conveys any impression of its actual physical composition.

Some of these equivalents are the Middle High German "Slöze," the German "schlosse," and the Norwegian "sletta"—the latter

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meaning "to slap," and having reference, probably, to the beating or driving of the sleet under the influence of strong winds. Sleet and hail are distinct, both formatively and structurally, as hail, being formed by a violent uprush of warm air into a much colder air mass, occurs almost uniformly during summer thunderstorms. Sleet pellets are not usually symmetrical in form, while hailstones are frequently so, being composed of a central nucleus of snow surrounded by concentric spheres of water and snow in alternate layers. However, for practical purposes, it is not a serious error to define winter hail as sleet.

The true sleet usually consists of considerable water in addition to the ice pellets, the pellets being of irregular formation, but at times it consists entirely of round, dry pellets, about the size of duck shot, which either remain dry and loose on the surface for a considerable time, or, if the surface is slightly warmer, unite into larger and very irregular masses of ice. This has been termed "ice rain." The dry sleet is probably due to the unusually low temperature of the lower air stratum.

Geographical distribution.—The region of greatest frequency was found to be over the lower Missouri, the lower Arkansas, the middle Mississippi, and the lower and middle Ohio Valleys, the southern Upper Lake and the Lower Lake regions, New England, the Middle Atlantic States, and central North Carolina, corresponding in the main to that portion of the country traversed by the *principal* LOWS, with cold northerly winds to the northward, and warm southerly ones to the southward, necessary precedents to sleet formation.

The area of maximum frequency (6 to 6.7 a year) covers northern and eastern Missouri and southern Illinois, although the absolute maximum of 7.7 storms a year occurred over south-central Pennsylvania. (See fig. 167.) An occasional storm of moderate character occurred over extreme northern Florida and along the Gulf coast, while over the interior of the South the annual average was less than two, *as a rule.* However, a local tendency toward a higher average (2.7 to 3.4) was noted over the more elevated regions of northwestern Georgia and southeastern Tennessee. West of the ninety-seventh meridian and over the northern Upper Lake region the average annual frequency was less than two, *as a rule*, except over southern upper Michigan, where the annual average, as indicated by the figures at Escanaba, was 4.9, and at Duluth, where the figures were 2.4. The low averages over the northern Upper Lake region were doubtless due to the equalizing effects of the water temperatures, and the local increases at Escanaba and Duluth support this contention, as the northerly winds blow entirely from the colder land surfaces at Escanaba, and over only a small area of

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water surface at Duluth, except when the winds are from the northeast.

The comparatively high figures of 3.4 over the northeastern portion of eastern Texas may be attributed to the operation of the same general conditions that created the maximum frequency over the great central valleys, etc.

Seasonal distribution.—The seasonal distribution of sleet and ice storms is not very well defined. In general January and February are the months of greatest frequency over the lower Missouri, middle Mississippi, and the Ohio Valleys, the Lower Lakes, and the Middle Atlantic States, while March and December are the months of greatest frequency over the Upper Lakes, especially the month first named. It should be remarked, however, that these Upper Lakes storms are rarely so severe as those in the region of the great river valleys and that the latter section, together with the Middle Atlantic States, probably comprises the great belt of severe sleet storms of the country. A fair proportion of the storms occurred in April, all above latitude 42½°, except in a few isolated places, notably on April 28, 1908, in the Panhandle of Texas and on April 20, 1904, at Charlotte, N. C., the latter being a very moderate one. Three May storms occurred at about latitude 47° and there were five October storms at widely scattered places, that of October 3 and 4, 1914, at Havre, Mont., being of severe character.

On the whole it may be said that severe sleet and ice storms may be expected at any time from November to March, inclusive, and occasionally, north of latitude 42°, during April and October. The probability of May storms may be disregarded on account of their very infrequent occurrence.

METEOROLOGICAL CONDITIONS FAVORABLE FOR OCCURRENCE OF SLEET AND ICE STORMS.

The following meteorological conditions, as indicated on the weather maps, appear to precede sleet and ice storms:

1. Low temperature and high pressure to the northward (between northwest and northeast).

Seventy-two per cent of the cases examined were well developed and 28 per cent fairly so; there were no failures.

2. Steep pressure and temperature gradients to the northward (between northwest and northeast); 69 per cent of the cases were well developed, 12 per cent fairly so, and 19 per cent failed.

3. Surface temperatures below the freezing point, usually between 22° and 28°; that is to say, surface temperatures between 22° and 28° 24 to 36 hours later. In other words, with other conditions favorable for sleet formation it will be likely to occur where the tempera-

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tures 24 to 36 hours later will be from 22° to 28°. This involves an accurate temperature forecast. Severe sleet with surface temperatures above the freezing point is practically unknown.

4. Moderately high pressure and high temperatures over the east Gulf and South Atlantic States. This condition was fulfilled in 70 per cent of the cases and failed in 30 per cent. A few of the HIGHS were cool and in a few instances there was a southeast LOW instead of a HIGH.

5. Northward looping of the isotherms (surface inversion); 88 per cent true, failing in only 12 per cent of the cases.

6. Gentle to fresh northerly winds, northwest to northeast, increasing by the time the sleet begins. This was found to be almost uniformly true. The winds were rarely light and even less frequently strong.

7. Low-pressure trough trending southwest to northeast between two HIGHS. The LOW is usually moving from the southwest, but sometimes from the northwest.

This appears to be a general rule except over the districts from the Southwestern States northeastward through the Ohio Valley, where the trough was absent about as often as it was present.

CONCLUSIONS.

This text is accompanied by several maps that indicate typical sleet conditions, one series for the interior and one for the Atlantic States. (See figs. 168–170.)

At best the forecasting of sleet is a difficult and very unsatisfactory undertaking, but such forecasting would be valuable if it could be done with a considerable degree of success.

FOG.

Foreword.—Fog may be defined as a surface cloud, and is caused (1) by the mixing of two bodies of air of unequal temperatures, one or both of which has a high vapor content, and (2) by the cooling of a body of moist air to a temperature lower than its dew point. During nighttime in warm seasons fog may form over lakes and rivers by the continued evaporation of the warm water, even though the cool overlying air is saturated.

Its character, distribution, and extent depend, of course, upon the character, distribution, and intensity of the contributory physical conditions, and it is proposed in this chapter to discuss these physical conditions as they appear on the weather charts, with a view to forecasting the fogs on the ocean and Gulf coasts and on the Great Lakes, where they constitute a frequent and dangerous menace to

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navigation. Fogs in the river valleys will not be considered, as they are more local in character, usually appearing during the night as a consequence of radiation of heat and disappearing within a few hours after sunrise, and on the navigable rivers they cause nothing more than a little delay and inconvenience, as river craft tie up during the prevalence of fog.

Naturally fogs are most prevalent along the shores of lakes and oceans, over rivers, and at times over such definite areas of the oceans as are near the boundaries of countercurrents of different temperatures.

GREAT LAKES REGION.

Seasonal distribution of fog.—Over the Upper Lakes, as a whole, February is the month of greatest fog frequency, while not far behind are January, June, and December, about alike with respect to the number of foggy days. Over Lake Superior and northern Michigan the seasonal distribution is not so well defined. The months of least frequency are July and August. The northern portion of the Upper Lake region is much less subject to fog than the southern portion, the ratio being about 1 to 6. The reason for this marked difference lies partly in the lesser frequency of sharp temperature contrasts over the northern sections, owing to the comparatively greater extent of water surface, but the difference is mainly due to the fact that, as a rule, neither the HIGHS nor the LOWS are to the northward of Lake Superior, and that the winds do not blow over the water surfaces.

February is also the month of greatest fog frequency over the Lower Lakes, the excess in frequency of fog in that month being much more marked than over the Upper Lakes. March is second, closely followed by January, April, and November. As on the Upper Lakes the months of least frequency are July and August. Of the two Lower Lakes, Erie has about 2 dense fogs to 1 for Lake Ontario, the difference probably being due to the difference in extent of water surface covered by easterly winds.

The most marked difference between the Upper and the Lower Lakes with respect to monthly fog distribution was noticed during June. On the Upper Lakes fogs were about as frequent in June as in January and December, while on the Lower Lakes they were less frequent in June than in any other months, except July, August, and October.

Conditions favorable for fog formation.—(1) On the Upper Lakes fogs are usually preceded by low pressure on the leeward side of the Lakes and relatively high pressure on the windward side, with a weak pressure gradient, not greater than 0.10 inch to 100 miles, and usually

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less, averaging, perhaps, about 0.10 inch to 250 miles. The gradient is usually least with southeast winds.

Quite often the isobars on the weather chart will be irregular in shape, with a gradient of about 0.10 inch to 150–200 miles, the isobars curving away from each other, leaving an open space between sometimes several hundred miles in diameter. This distribution is also a perfect rain type for the open section. Frequently with this formation there will also be observed a northward looping of the isotherms, similar to that observed before thunderstorms, indicating an unstable temperature distribution, which, however, does not appear to be an essential condition for fog formation.

The height of the barometer is not important for fog formation, and at Chicago dense fog has occurred with pressure as high as 30.80 inches and as low as 29.25 inches. In summer the pressure is usually low, for with high pressure the sharper temperature contrasts between the water and the land cause stronger winds, thereby preventing the formation of fogs.

(2) Temperature differences more or less marked between the water and land surfaces. The water temperatures were the lower in about two-thirds of the fog periods, without regard to the season of the year, although some general tendencies toward higher Lake temperatures were noticed over the southwestern section during May and November.

(3) Relative humidity above normal, averaging above 90 per cent, although lower in quite a fair percentage of the cases observed (only 52 per cent at Chicago preceding the local fog of Sept. 10, 1888). The high humidities also prevail for a considerable distance inland in the direction of the LOWS. Low humidity fogs are very local.

(4) The occurrence of precipitation from 24 to 36 hours previous to the fog, usually to the westward and southwestward of the Lakes, toward the LOWS, as perhaps only about 10 per cent of the LOWS are found over Lake Superior or the Michigan Peninsula. The precipitation in the LOWS generally continues while the fogs prevail in the Lake region, as the surface temperatures are higher and the moisture content of the air is greater in the LOWS. It is also noticed that frequently the fog belt extends westward from the Lakes into the Mississippi and lower Missouri valleys, and at times even farther westward and southwestward when the temperature contrasts are not so marked. Quite often dense fog will be observed at one place in the great river valleys with rain falling at another place near by.

(5) Low wind velocities, less than 15 miles an hour, usually less than 10 miles, and about one-third of the time less than 6 miles. Fogs with winds above 15 miles an hour have their characteristics very well marked, and they occur usually in the spring and autumn, with the Lake temperatures almost invariably the higher. However,

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during winter fogs with winds above 15 miles an hour the Lake temperatures are often the lower.

The antecedent conditions necessary for the formation of fog along the Lower Lakes are much the same as for the Upper Lakes. There is noted, however, a tendency toward less fog over Lake Ontario, particularly the eastern portion, than over Lake Erie, the deficiency being most marked with southeast winds, which, as a rule, are not followed by fog unless the winds are quite warm (above 40° in winter and about 50° or 60° in summer).

MISCELLANEOUS OBSERVATIONS.

(1) It is noticed that the belt of maximum fog frequency extends from about the southern third of Lake Michigan eastward to Lake St. Clair and extreme southern Lake Huron, and thence over western Lake Erie; probably because the conditions necessary for fog formations are more frequently and more completely fulfilled here than over other portions of the Great Lakes region, particularly with respect to the location of the high and low areas, and to the greater frequency and extent of the temperature differences.

(2) A maximum of fog frequency occurs at Chicago, dense fog often occurring at that place with none elsewhere along the Lakes. It is doubtless a purely local condition at such times, due to an excess of smoke, and is likely to occur even though the necessary antecedent conditions are not fully defined. These fogs are usually shallow, and at times do not extend above the tops of high buildings.

(3) Fogs usually occur in the form of an uniform covering like a blanket, but at times, frequently on Lake Superior, they form in banks or bands, both along the shore and over the water. Sometimes they form in comparatively narrow bands over the water with intervening areas of clear weather. In this connection the following extract from "The Meteorological Chart of the Great Lakes for the Season of 1899" (Henry and Conger), is of interest and value:

> It appears that fog does not generally appear in the blanket form, except when LOWS are moving slowly toward the lakes. The most frequent formation reported is the heavy banks, which are seen in their best form on Lake Superior. These banks appear frequently on the lakes, with intervals of clear weather. Fog also appears in the belt or band formation, viz. a narrow band which extends for many miles in length.
>
> This formation is also most frequent on Lake Superior. One vessel will run for hours in the bank formation, while another vessel, several miles distant, running parallel, will be in clear weather and can hear the fog whistle of the steamer in the fog, and also see the wall of the fog bank. These formations are most frequently reported during the summer months. It has been found that the approach of a LOW from the west of Lake Superior will cause fog to form over the western end of that lake. The fog appears to move eastward in the lifting conditions, so that, as before stated, one steamer will make

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the run eastward on Lake Superior in fog, while one following a few hours later will not encounter any, indicating that the fog banks move steadily eastward. Masters have reported that less fog was encountered after passing Sable Point, Lake Superior, on the Marquette, or Portage Entry, route than on the passage around Keweenaw Point. The reports appear to bear out this statement, in view of the fact that much less fog is reported from Marquette, or Portage Entry, and Houghton than from the Keweenaw Point route. The reports indicate that the most fog on Lake Superior is encountered between Whitefish Point and Keweenaw Point, and it is probable that vessel masters would encounter less fog by taking the Portage Entry course in preference to that around Keweenaw Point. This would probably be the case during the summer months, when fog is most frequently encountered on Superior.

The foregoing statement appears to indicate that fogs are much more prevalent over the waters of Lake Superior than along the shore, as over the latter section the summer months are those of least fog frequency, especially along the extreme western shores of Lake Superior.

Atlantic coast fog frequency.—Naturally, fog will be most frequent where the differences in temperature between the land and the water are most persistent, so that on the Atlantic coast the region of maximum frequency would be the New England coast. The records for the 14 years from 1900 to 1913, inclusive, indicate that, with a few explainable exceptions, the region of maximum frequency is the eastern coast of Maine, and that there is a steady decrease southward to Key West, Fla., where dense fogs are very rare. The diagram (Fig. 171) shows the number of days on which dense fog occurred along the Atlantic coast from 1900 to 1913, inclusive:

The great excess at Nantucket and the smaller one at Block Island are due to the fact that they are small islands, and fog will therefore occur at any time when the winds are comparatively light and the temperature difference between the land and the water is sufficiently marked. This condition naturally occurs most frequently during the summer months.

The relatively small number of foggy days at New Haven and New York is no doubt due to the great preponderance of land area as compared with that of the water, and the fogs are least frequent in summer when the mean land and water temperatures do not differ greatly. The excess at Cape May over Atlantic City probably arises from the fact that Cape May is situated at the end of a narrow point of land with water on three sides, making the conditions much similar to those at Nantucket and Block Island. It should also be noted that the period of minimum frequency is the autumn and early winter, just as at Nantucket and Block Island. The tendency toward an increase in fog frequency at Cape Henry is probably due to the fact that the topographical conditions are of the same character, but not so pronounced as at Cape May, Block Island, and Nantucket.

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Another increasing tendency at Charleston is somewhat more difficult of explanation. There is a preponderance of water surface in the vicinity, although the bay forming Charleston Harbor is not of great extent. There is, however, water on all sides of the city except between north and northwest, and this probably accounts for the excess of foggy days. At Key West the land temperatures are uniformly lower, and the mean land and water temperatures are so nearly alike that it is almost impossible for fog to form. With light winds

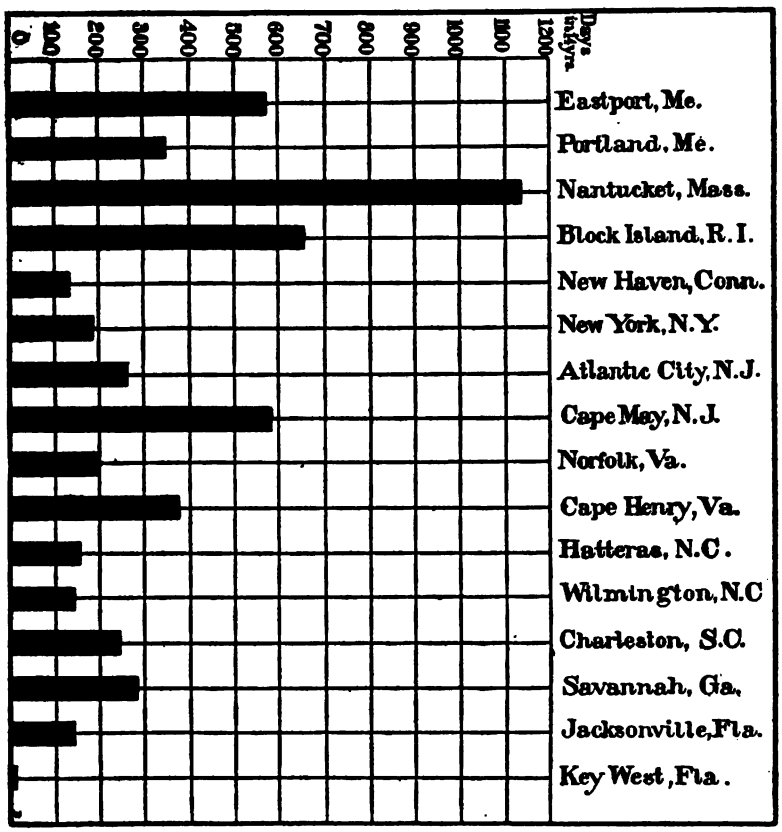

FIG. 171.—Fog frequency, Atlantic coast.

and high humidity fog will form at times when there is a strong HIGH over the central and northern portions of the country, accompanied by a cold wave, bringing down cool winds from some northerly point, preferably the northeast, upon the warm Gulf waters.

It will be noticed that no mention has been made of dense fogs at Boston. There were only 125 recorded during the 14 years under observation, but it is almost certain that over Massachusetts Bay and the coast immediately adjoining the fogs were as prevalent as over

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many other portions of the New England coast. Boston is more or less sheltered from the open water except in a due easterly or southeasterly direction, and this should account for the lesser fog frequency.

It appears that the observations reasonably justify the following general precepts for the Atlantic coast.

1. Fogs are most frequent where the mean water temparatures are lowest.

2. Other things being equal, fog frequency in any given locality is proportional to the differences in temperature between the land and the water surfaces.

It must be mentioned, however, that these precepts, so far as the Great Lakes are concerned, are not so general in their application. No. 2 is generally applicable, but No. 1 is not at all so.

Geographic distribution of fogs.—As the occurrence of fog is almost entirely a question of pressure distribution and resulting wind direction, it reasonably follows that there will be wide differences in the duration and geographical extent of fog belts. At times, not often it is true, the fog belt will extend along the entire Atlantic coast from Eastport to Jacksonville, and westward along the Gulf coast from Tampa to the mouth of the Rio Grande. At other times the fog belt will extend from the Maine coast to Jacksonville, Cape Hatteras, Cape Henry, Cape May, New York, or to Block Island. Quite frequently it will be confined to the Maine coast, especially the eastern portions; occurring whenever light southerly winds blow, with a maximum frequency in midsummer, when the temperature differences are greatest. These Maine fogs, especially on the eastern coast, are sometimes very fleeting, disappearing and reappearing with variable winds at intervals of a few minutes.

Again there will be a fog belt that will extend from Nantucket southward to Cape May, Cape Henry, or to Cape Hatteras, and again to Savannah and Jacksonville. Other belts extend from New York southward along the New Jersey coast, and at times as far as Hatteras. Again, there is the fog belt that extends from Cape May to Cape Henry, from Cape Henry or Cape Hatteras to Jacksonville, and from Charleston or Savannah to Jacksonville. Still another type of fog belt extends along the ocean from northeast to southwest, touching the coast at only a few points, such as Eastport, Nantucket, Cape May, and Cape Hatteras.

Seasonal distribution.—The percentage of foggy days for each month, based upon the total number of such days for the station discussed, and for the entire period from 1900 to 1913, inclusive, together with the monthly mean land and water temperatures, are shown in Tables 1 and 2.

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TABLE 1.—*Seasonal distribution of foggy days, in percentages of the total number observed at each station.*

	Eastport, Me.	Portland, Me.	Nantucket, Mass.	New York, N. Y.	Atlantic City, N. J.	Norfolk, Va.	Wilming, N.-C.	Charleston, S. C.	Savannah, Ga.	Jacksonville, Fla.	Key West, Fla.
Total number of foggy days.....	574	346	1,136	186	259	198	142	249	184	140	3
January.....per cent..	3	7	6	20	11	14	17	20	20	32	0
February.....do....	3	1	5	7	7	11	11	16	15	14	67
March.....do....	4	5	9	15	15	12	12	15	13	8	0
April.....do....	6	10	8	8	10	4	6	3	7	4	0
May.....do....	11	10	12	11	17	8	5	4	5	1	0
June.....do....	12	9	13	3	12	3	2	1	1	1	0
July.....do....	23	12	15	1	1	1	1	1	1	1	0
August.....do....	18	13	11	1	2	2	2	2	1	1	0
September.....do....	11	12	10	6	6	6	9	6	5	1	0
October.....do....	6	11	5	7	5	12	11	8	5	4	0
November.....do....	1	7	4	8	8	15	11	10	12	11	0
December.....do....	2	3	2	13	6	12	13	14	15	22	33

TABLE 2.—*Mean land and water temperatures.*

	Eastport, Me.	Portland, Me.	Nantucket, Mass.	New York, N. Y.	Atlantic City, N. J.	Norfolk, Va.	Wilmington, N. C.	Charleston, S. C.	Savannah, Ga.	Jacksonville, Fla.	Key West, Fla.
January:											
Land	20.1	22.0	32.2	30.2	32.5	40.4	45.6	49.3	49.9	53.9	68.8
Water	35.9	33.4	37.1	33.4	35.8	41.2	47.7	50.7	49.9	57.9	72.0
February:											
Land	21.5	33.8	31.0	30.7	33.0	41.8	47.7	51.6	52.5	56.9	70.8
Water	33.1	32.0	34.6	32.6	37.0	44.5	50.4	53.2	53.4	61.0	73.6
March:											
Land	28.9	32.1	36.7	37.5	38.9	47.8	53.7	57.2	58.3	61.9	72.7
Water	32.7	33.5	36.5	35.6	39.7	49.5	55.4	57.9	58.4	66.4	75.7
April:											
Land	38.4	42.9	43.9	48.1	47.5	56.0	60.4	63.8	64.7	67.6	75.5
Water	35.5	39.2	42.5	43.6	47.7	56.1	62.5	64.2	64.6	71.3	78.8
May:											
Land	46.9	53.5	52.7	59.3	57.5	66.1	69.1	72.5	72.6	74.2	79.0
Water	39.1	47.0	49.8	54.8	56.2	67.3	71.7	73.1	73.1	78.3	82.8
June:											
Land	54.4	62.6	60.8	68.5	66.8	74.4	75.5	78.5	78.2	79.0	82.2
Water	42.9	54.8	58.4	65.9	65.7	76.0	78.8	80.0	80.0	83.4	86.1
July:											
Land	59.8	68.0	67.5	73.5	72.5	78.4	78.7	81.3	80.5	80.9	83.7
Water	46.8	59.6	65.5	72.4	72.1	80.9	83.8	83.6	84.5	86.6	87.4
August:											
Land	59.8	66.1	67.8	72.2	72.6	76.7	77.6	80.3	79.4	80.1	83.8
Water	49.8	61.0	67.2	73.3	72.8	80.5	81.5	83.2	83.0	85.5	86.6
September:											
Land	55.2	59.5	63.5	66.5	67.7	71.7	73.1	76.4	75.4	77.4	82.5
Water	50.6	57.8	64.5	69.3	71.0	74.8	77.0	78.9	78.4	82.3	86.1
October:											
Land	46.6	49.1	54.6	55.5	57.3	61.3	63.3	67.0	66.2	69.6	78.7
Water	49.8	52.3	57.7	60.1	62.3	65.3	69.3	71.1	71.0	75.3	81.4
November:											
Land	36.8	37.7	45.7	44.0	45.5	51.2	54.1	58.1	57.5	61.3	74.3
Water	46.2	44.6	49.8	48.5	52.3	54.4	59.5	59.5	60.2	67.3	76.6
December:											
Land	25.3	27.2	37.0	34.4	36.4	43.1	47.2	51.2	51.3	55.1	70.0
Water	41.0	36.9	41.7	38.4	41.4	44.0	49.9	53.2	50.6	59.0	71.2

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An inspection of this table shows that on the open New England coast fogs are most frequent in midsummer and least frequent in winter, although when Block Island is reached there is a shift in the time of maximum frequency toward early summer. Forty-one per cent of the total number of fogs occur from June to August, inclusive, while in December, January, and February the percentage is only 11. The spring percentage is 28 and that of the autumn 20.

Along Long Island Sound and the middle and south Atlantic coasts the season of maximum frequency shifts to winter and early spring (late spring along the extreme southern coast of New Jersey, probably on account of the lower water temperatures and the prevailing winds from the water surfaces to the eastward, southward, and westward—Delaware Bay being only a short distance to the westward). Likewise the season of minimum frequency changes to midsummer. From New Haven southward, except along the extreme southern New Jersey coast and at Key West, the seasonal percentages are: Winter, 46; spring, 27; summer, 5; and autumn, 22. From Hatteras to Jacksonville the mean summer percentage is only 3.4. Here the land temperatures, while from 3° to 6° lower than those of the water, are nevertheless quite high (75 to 81) and consequently have a large moisture capacity. Therefore the slight differences in temperature that would be caused by the intermixing of the sea and land airs would not be sufficient to cause condensation.

NECESSARY CONDITIONS PRECEDENT TO FOG FORMATION.

These are found to be practically the same as those for the Great Lakes, and it not infrequently happens that certain well-marked conditions will be followed by dense fog on both the Lakes and along the Atlantic, even the Gulf coast. (See maps Jan. 18–19, 1900, figs. 172 and 173.)

Conditions favorable for fog formation are:

(1) Low pressure to the leeward side with weak pressure gradients.

(2) Temperature differences between land and water surfaces fairly well marked.

(3) High humidity.

(4) Occurrence of precipitation in the direction of the low pressure.

(5) Low wind velocities, less than 15 miles, and usually less than 10 miles an hour.

Low barometric pressure to the leeward side with weak gradients appears to be the *sine qua non* with regard to fog formation, except in a few localities such as Nantucket, where fog will form at any

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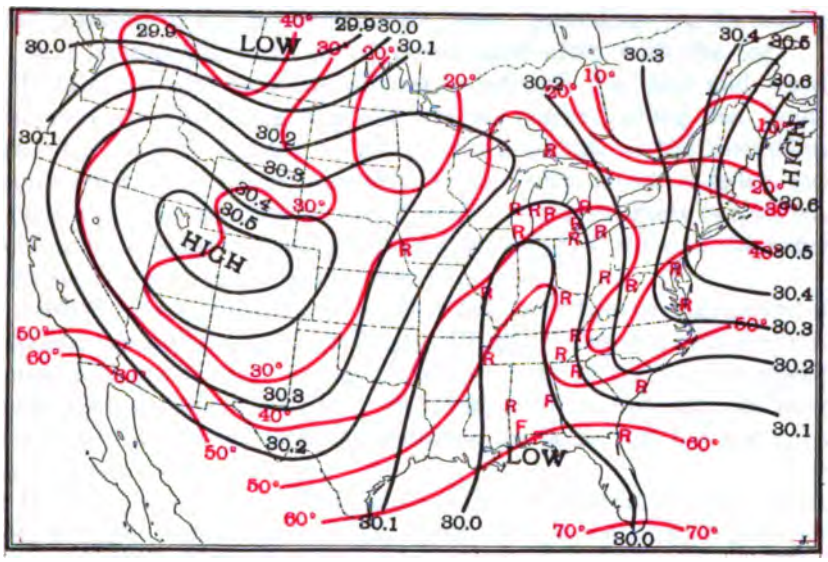

FIG. 172.—Fog types, interior valleys, January 18, 1900. R, rain; F, fog.

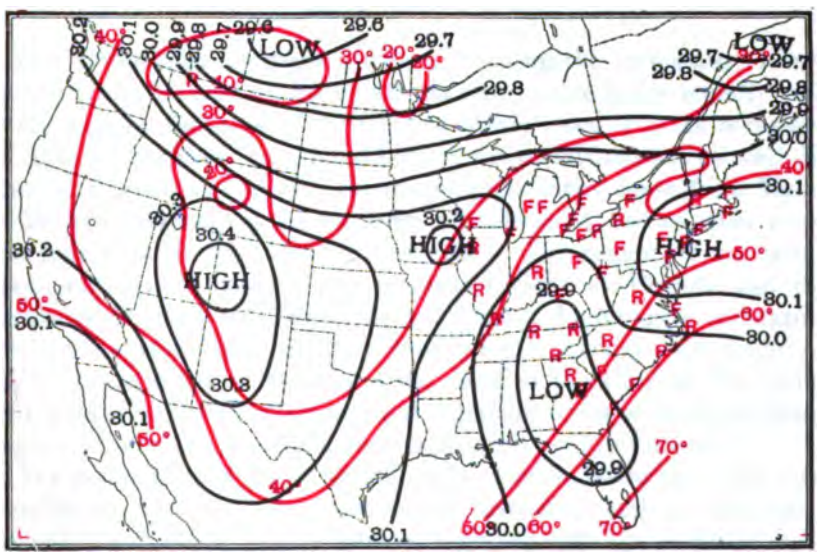

FIG. 173.—Fog types, interior valleys, January 19, 1900. R, rain; F, fog.

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time when pressure conditions are stagnant and temperature differences will cause sufficient change in wind direction to cause fog.

With slight LOWS in the Southwest there is not apt to be much precipitation in the South Atlantic States preceding fog formation in that section, although it will occur quite often with the fog.

It is noted also that the difference between the land and water temperatures preceding fog are not so marked along the South Atlantic coast as farther to the northward, but, as the prevailing winds are from the water and are, consequently, moisture laden, and as the water temperatures are uniformly the higher, there is sufficient cooling by mixing to cause partial condensation of some of the vapor into fog during the cooler months of the year.

Low wind velocities are essential to the formation of fog, except in extreme cases along the New England coast, where fog will occur at times with moderately strong easterly winds, if the land temperatures are considerably higher, with rather low humidity. In these instances there is sufficient condensation to cause fog, but not quite enough to form rain.

It seems, therefore, that of the conditions mentioned above, numbers 1, 3, and 5 are, with very few exceptions, essential to fog formation, while Nos. 2 and 4 are quite essential along the northern, but not along the southern, coast of the Atlantic Ocean.

GULF OF MEXICO FOGS.

It is found that the general rules governing the formation of fogs on the Great Lakes and the South Atlantic coast apply equally well to the fogs on the coast of the Gulf of Mexico, and it is not necessary to repeat them here. As stated before, the conditions are so well defined at times that fogs will occur along the entire coast from Maine to Texas, except along the southern Florida coast, but at other times the fogs will be very local in character. The region of maximum frequency occurs between the northwest coast of Florida and the northeastern coast of Texas, the number of foggy days increasing toward the west. The regions of minimum frequency were found on the southern coast of Texas and the coast of the Florida Peninsula. The diagram (see fig. 174) shows the number of days on which dense fog occurred along the Gulf coast from 1900 to 1913, inclusive.

The percentage of foggy days for each month, based upon the total number of such days for each station discussed, and for the entire period from 1900 to 1913, inclusive, together with the monthly mean land and water temperatures, is shown in Tables 3 and 4.

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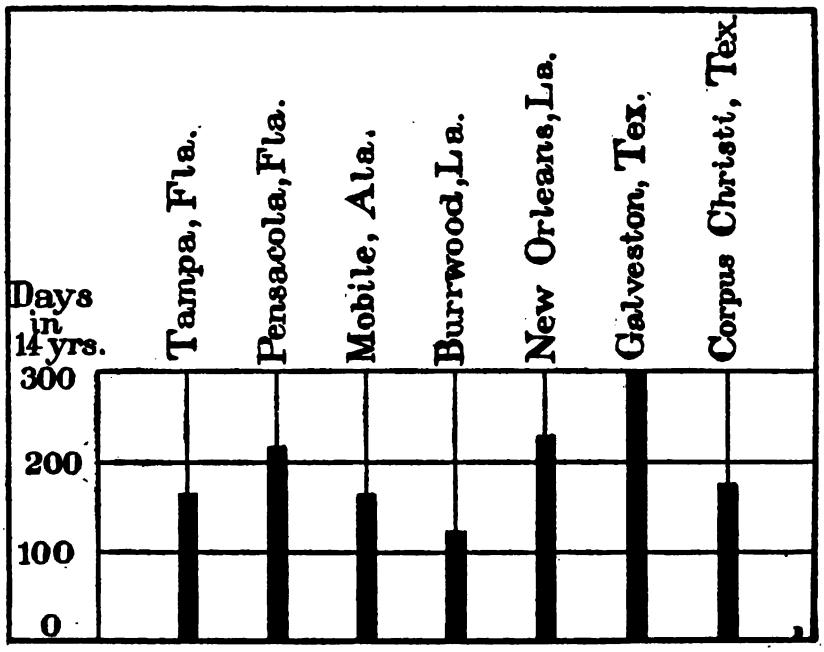

FIG. 174.—Fog frequency, Gulf coast.

TABLE 3.—*Seasonal distribution of foggy days, in percentages of the total number observed at each station.*

	Tampa, Fla.	Pensacola, Fla.	Mobile, Ala.	Galveston, Tex.	Corpus Christi, Tex.
Total number of foggy days	162	220	159	301	166
January ..... per cent	30	22	27	28	25
February ..... do	18	18	12	18	13
March ..... do	14	24	21	24	17
April ..... do	3	7	7	8	2
May ..... do	2	3	3	1	2
June ..... do	0	1	1	0	0
July ..... do	0	0	0	0	0
August ..... do	1	0	0	0	1
September ..... do	2	0	1	0	1
October ..... do	5	1	3	3	10
November ..... do	14	12	11	8	12
December ..... do	11	12	14	10	17

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TABLE 4.—*Mean land and water temperatures (in degrees Fahrenheit).*

	Tampa, Fla.	Pensacola, Fla.	Mobile, Ala.	Galveston, Tex.	Corpus Christi, Tex.
January:					
Land	57.4	52.2	49.8	52.7	55.3
Water	59.9	55.3	50.9	54.3	52.8
February:					
Land	60.9	55.4	53.2	55.6	57.1
Water	63.7	60.4	54.3	57.2	58.6
March:					
Land	65.9	61.1	59.2	62.3	64.0
Water	66.6	63.4	59.1	63.8	65.4
April:					
Land	69.2	67.6	65.9	68.7	70.8
Water	72.6	70.9	65.6	71.0	71.9
May:					
Land	75.5	75.0	73.6	75.4	76.3
Water	79.0	78.0	74.3	78.2	78.1
June:					
Land	78.7	80.1	79.2	81.0	80.5
Water	83.4	83.3	82.4	84.4	84.6
July:					
Land	79.9	81.3	80.5	83.0	81.9
Water	85.9	85.2	85.8	86.5	86.5
August:					
Land	80.0	81.0	79.7	82.6	81.7
Water	85.6	85.0	85.0	85.8	86.9
September:					
Land	78.3	78.2	76.6	79.4	79.3
Water	84.2	82.6	81.9	81.6	82.8
October:					
Land	72.6	69.5	67.1	72.4	72.9
Water	76.9	76.1	74.2	75.5	77.2
November:					
Land	65.4	59.8	57.6	62.9	63.8
Water	66.8	64.9	63.4	64.3	65.9
December:					
Land	59.4	53.8	51.4	56.3	57.1
Water	60.6	57.5	53.3	57.6	59.6

It will be seen that the fogs were most frequent in winter and least in summer, being of very rare occurrence from June to September, inclusive. January is the month of maximum frequency, while no dense fogs at all were reported during July.

The seasonal percentages are as follows: Winter 54, spring 30, summer 1, autumn 15. The almost total absence of summer fog is due to the same causes that create a similar absence on the south Atlantic coast, namely, high temperatures and high vapor content.

The wind directions preceding and accompanying the Gulf fogs are not so uniformly from the water toward the land, nor from the cool toward the warm air, although in a majority of the cases the winds blew from the water surfaces—that is, from a warmer region to the southward and southeastward. In many instances exactly the opposite conditions prevailed, and fog would form when a cold wave covered the land and the cool north and northeast winds would blow down to the much warmer Gulf water, causing partial condensation in the form of fog, that would at times extend over the Gulf for a considerable distance.

This is the prevailing type for Florida Peninsula fogs, including Key West. The a. m. map of January 22, 1908 (fig. 175), affords a good type of fog formation from cool north winds, but, unfortu-

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nately, the pressure distribution on the previous day was not such as to indicate on the following morning the presence of a cool HIGH over the great central valleys and light north winds down to the Gulf. In fact, east and southeast winds were indicated, but with land and water temperatures about equal. A rare but well-marked type, favorable for fog formation on the Gulf coast, is one with relatively *cool* southerly winds blowing from the Gulf, and such a condition occurred on January 24, 1909. On the 23d temperatures were abnormally high over the Ohio Valley and the interior of the Gulf States, and on the morning of the 24th dense fog occurred from Galveston eastward to the northwest Florida coast, and on the Atlantic coast from Jacksonville to Charleston, also extending into the interior of Alabama, Georgia, and South Carolina. The fog, however, was only a morning fog, and soon disappeared under the influence of the sunlight.

General notes.—1. Quite often fog belts appear to travel, generally from west to east along the Gulf coast and from southwest to northeast along the Atlantic coast; occasionally the travel will be in the opposite directions. By "traveling" is meant the movement, usually east or northeast, of a fog belt on the succeeding day or days and not necessarily continuing over the section first covered. The condition is usually indicated in accordance with the general rules for fog formation, being naturally associated with the eastward pressure drift.

2. A good fog type for the South Atlantic and Gulf coasts—high pressure over Bermuda and low over Texas and Oklahoma, with very weak gradient.

3. Fogs form quite frequently on the Atlantic coast with a LOW to the northward of Lake Superior and moving northeastward. The LOW appears to *open up* and leave a trough with weak gradients to the southwestward and quite often with a moderate LOW on the Texas coast.

4. Differences between the land and water temperatures are not so marked along the Atlantic and Gulf coasts as along the Great Lakes, and fog forms with nearly equal temperatures when the latter do not differ sufficiently to cause complete condensation in the form of rain or snow. Frequently rain will be falling at one place on the coast while at the next station, only a short distance away, there will be dense fog. It is usually observed, however, that at the place where the rain is falling the wind velocity is greater than where the fog prevails and a decrease in the velocity would doubtless be at once followed by fog.

5. The fog belt is not always continuous along a coast. It will frequently fail to form in a locality, yet dense fog may prevail on both

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sides. Local conditions are probably the cause of this, either irregularities in wind direction or velocity or in pressure distribution.

6. The morning map of January 23, 1909, shows an excellent fog type from warm southerly winds for the Lake region, Middle Atlantic States, and New England. Although the barometric gradient was quite steep to the east, the LOW *is long drawn out to the west*, with practically no gradient.

PACIFIC COAST FOGS.

For information regarding the Pacific coast fogs the writer is indebted to the officials in charge of the local office of the Weather Bureau at Portland, Oreg., and San Francisco, Los Angeles, and San Diego, Cal.

Washington and Oregon.—The months of maximum frequency are July and September and those of least frequency February, April, and December. Fogs are reasonably frequent in June and October and quite uncommon in January, March, May, and November.

The fogs are caused by the decrease in the land temperatures due to radiation so that they become lower than the water temperatures. This statement, however, does not apply to the winter months, when the land temperatures during the prevalence of fog are the higher, and the fog is due to the mixing of air currents of different temperatures, moving with fair velocity.

The barometric gradient is weak and the winds usually light to moderate from southwest to northwest. At Tatoosh Island, Wash., the winds preceding fogs are generally from south or southwest, water winds, and blowing with a velocity about 20 miles an hour. At North Head, Wash., the winds are usually from the northwest (also water winds) and blow from 10 to 20 miles an hour.

Summer fogs appear about sunrise and disappear before noon, while winter fogs may form at any hour.

Northern California.—An interesting chapter on fog formation on the California coast will be found in Bulletin L, Weather Bureau (Prof. Alexander G. McAdie).

It may be stated as a general rule that fog will form at any time when a HIGH moves rapidly southward from Washington or Oregon, or northward from Mexico. Fog will occur to the southward of the axis of the southward moving HIGH and to the northward of the axis of the northward moving HIGH, that is, in front of the center of the HIGH.

During summer afternoons the temperature gradient between the coast and valley regions will often be as much as 50°, and fog will then form along the coast without regard to the pressure distribution.

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At times fog will occur following an inversion of temperature, but inversion data are not available except at San Francisco. Here it is found that if the morning temperature at Mount Tamalpais is 8° or more higher than that at San Francisco, fog will form on the coast within 24 hours. If the temperature differences are great, fog will probably follow during the same afternoon or evening.

The only pressure distribution types for summer are (1) an ocean HIGH over the Mexico or south California coast, with a slow northward movement, and (2) a HIGH moving down along the coast from the northward, attended by fresh westerly winds.

Southern California.—The pressure distribution type favorable for fog formation appears to be a HIGH on the North Pacific coast, moving south or southeastward, with moderately low pressure over extreme southern California or Mexico. The fogs are usually night fogs, practically none occurring between 9 a. m. and 6 p. m. Following periods of high temperatures fog banks are likely to form some distance to seaward toward the middle of the day, and move in to the shore at night, disappearing early on the following day.

Except at Redondo Beach, local configuration does not favor fog formation from well-marked indrafts, such as prevail in the vicinity of San Francisco.

Following will be found some additional maps illustrating the meteorological conditions prevailing before and during the occurrence of dense fogs in the interior valleys and over the Great Lakes. (See figs. 176 and 177.)

THUNDERSTORMS.

At least three-fourths of the summer precipitation in the United States east of the one hundred and fifth meridian is in the form of showers, with or without thunder; the majority, however, with thunder. Hence what has been said hereinbefore concerning forecasts of precipitation during the summer applies equally well to forecasting thunderstorms.

It will be remembered that the steep barometric gradients and strong winds of winter give way to weak gradients and practically a stagnant atmosphere in summer. To these conditions there must be added high humidity and greatly increased insolation, due to the change in season. The interior of the continent is now warmer than the adjacent oceans and the horizontal circulation is at a minimum. The vertical circulation, on the other hand, is at a maximum, and precipitation which in the winter season was mostly orographic or cyclonic, is now mostly convective. (See note on convective rains, page 113.)

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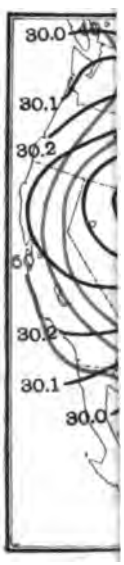

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Geographic distribution.—Roughly speaking, thunderstorms may occur in any part of this country, but they are infrequent in the Pacific coast and northern Plateau States; they are also infrequent in northern New England and the Lake Superior region. The region of greatest frequency is in the great interior valleys and the Florida Peninsula. They are frequent in the Rocky Mountain States from northern Wyoming south to central New Mexico.

The subject of geographic distribution is treated by the writer at greater length in Weather Bureau Bulletin Q (Climatology of the United States), to which the reader is referred.

Seasonal distribution.—In winter the region of thunderstorms is confined to the lower Mississippi Valley and along the Gulf coast. As the season advances they spread thence to the northward and westward over the Plains States, attaining their maximum frequency in May and June. East of the Appalachians the maximum frequency is not reached until July and August. In Florida and along the Gulf coast the maximum frequency occurs in the season of convectional rains. After July the frequency gradually diminishes to midwinter, when only sporadic cases occur in connection with LOWS that pass northeastward from the Gulf.

Diurnal variation.—Cox and Armington have compiled for Chicago and Fassig for Baltimore statistics of the occurrence of thunderstorms throughout the 24 hours. These statistics show that for Chicago the time of greatest frequency of storms is in the afternoon from 1 to 6 p. m.; at Baltimore it is also in the afternoon, with a marked maximum between the hours of 2 and 4 p. m.; at both Chicago and Baltimore there is a considerable number of thunderstorms during the first half of the night, viz, between 6 p. m. and midnight, the percentage occurring during that period being 31 and 32, respectively. This is explained on the ground that thunderstorms at both stations occur mostly in connection with moving LOWS or cyclones, whereas in lower latitudes cyclone control is less pronounced.

Relation of thunderstorms to pressure distribution.—Thunderstorms or thundershowers occur in connection with a number of types of pressure distribution. We can not hope to present a complete and trustworthy account of each of them, but we shall endeavor to point out the general principles which should guide the forecaster. In a calm, humid atmosphere, with morning temperatures 70° or over and pressures from 29.90 to 30 inches, the generation of thunderstorms is apparently an easy matter, and the likelihood of such storms occurring, especially over northern districts, is greatly increased by the presence of a weak cyclonic circulation over regions to the west or northwest or a system of weak opposing winds. High winds are inimical to the formation of severe thunderstorms.

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Perhaps the most favorable type of pressure distribution for thunderstorms in the Ohio Valley, the Lower Lake region, the Middle Atlantic and New England States is a shallow LOW that extends trough-shaped southwestward from the mouth of the St. Lawrence to the upper Ohio Valley, attended by a HIGH over Minnesota and a second HIGH over the Atlantic, the latter with its western end resting over the Carolinas. The weather maps of June 16–17, 1892, are good types. (See Weather Bureau Bulletin No. 9, "Report on Forecasting of Thunderstorms in 1892," by N. B. Conger.)

It has long been known that thunderstorms develop most readily in the southeastern quadrant of a circular or oval-shaped LOW, especially if both temperature and humidity in that region are relatively high. Any region of strong horizontal temperature contrasts within a short distance is favorable ground for the development of thunderstorms. The regions of surface inversion of temperature mentioned on page 260 by Prof. Frankenfield are indicated on the weather maps by a decided northward bending of the surface isotherms and a southward bending a short distance to the westward, thus indicating that the surface temperature over a limited area is higher than in adjoining areas in the same latitude. Such a condition, as shown by both observation and theory, is provocative of vertical convection, through which thunderstorms are produced. Another case much similar to the above is that of thunderstorms which occur on the shift of the wind in V-shaped depressions and on the eastern front of HIGHS that may be advancing into regions of relatively high temperature and humidity.

Thunderstorms with indefinite pressure distribution.—As illustrating the apparent lack of association with definite pressure distribution we have reproduced the series of p. m. weather maps, June 10–13, 1898 (figs. 178–181). The map of June 12 is characterized by an ill-defined trough of low pressure that extends somewhat crescent-shaped from Lake Huron to British Columbia, with three centers of low pressure, two of which can be shown only by drawing an isobar for a pressure difference of 0.05 inch, instead of 0.10 inch. Pressure is relatively high over the South Atlantic States and eastern Manitoba, and showers have occurred along the isobar of 29.90 from New England to eastern Kansas. On this map there have been entered the thunderstorm symbols at those points where such storms occurred between 8 a. m. and 8 p. m., June 13, corresponding to the second forecast period of the previous morning. The 8 p. m. map of June 13, 1898, (fig. 181), has also been reproduced (see the folder), largely to show the development during the preceding 12 hours; on that map the thunderstorm symbol has been entered against those stations reporting the occurrence of thunderstorms during the period 8 a. m. to 8 p. m., June 14, corresponding to the second forecast period of the

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morning map of the 12th (see fig. No. 181). These two maps may be considered as examples of maps wherein the details of pressure distribution are in a measure lost by the magnitude of the interval between consecutive isobars, viz, 0.10 inch. European meteorologists, in studying the occurrence of thunderstorms, have drawn isobars for an interval of a single millimeter and are thus able to bring out a number of details. It is often useful to sketch in lightly the isobars for an interval of 0.05 inch, particularly between the isobars of 29.90 and 30.10, as it is mostly between these limits that thunderstorms occur.

Thunderstorms in connection with Atlantic highs.—The weather maps of August 10–13, 1905 (figs. 182–185; see the folder), are reproduced as illustrating a type of late summer pressure distribution that is unusually effective in causing thunderstorms in the Middle and South Atlantic States and westward to Tennessee and Kentucky.

The genesis of HIGHS similar to the one illustrated is somewhat as follows:

In the late summer months HIGHS that drift slowly eastward along the northern circuit seem to take a southward course as soon as they reach the Atlantic, off New England. The extreme western end of the HIGH may encroach more or less on the land. In its southward movement along the coast it induces cool ocean winds and frequent showers over a portion of the South Atlantic States. The map of August 12, 1905, shows the center of the HIGH at Bermuda, with the isobar of 30.20 touching the continent at Hatteras. Note that the thunderstorms portrayed on that map occurred during the period 8 a. m. to 8 p. m. of the 13th, or in the second period of the forecast made on the morning of the 12th. (See figs. 182–185.)

It frequently happens that when the Atlantic is occupied by a HIGH off the Carolina coast the pressure gradient to the westward over the great interior valleys is very weak and the morning temperatures are 70° or more. Thunderstorms are likely to occur locally throughout the region of indifferent pressure gradients, regardless of the barometric configuration, so long as sea level pressure is between 29.90 and 30 inches or thereabouts. The advance of a western HIGH and cooler weather is almost invariably attended by general thunderstorms along the front of the cooler weather.

Thunderstorms generated by excessive temperature and high humidity.—The writer has noted that an isotherm of 80° on the morning map that is sometimes found as far north as New England and the Lower Lakes, in July, may continue for as many as three consecutive mornings; but about the afternoon of the third day there will be thunderstorms, with lower temperatures. The impression that these cases created is that abnormally high temperatures and

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high humidity in the morning in the Middle Atlantic States can not long endure without an overturning of the lower layers of the atmosphere, such as is produced by the thunderstorm. In this case the region of thunderstorms is along and near the area covered by the isotherm of 80°. (See weather maps, July 2, 1903; July 10–12, 1897.)

Forecasters are aware of the phenomenon of the breaking up of a heated spell by a series of thunderstorms. Many references thereto appear throughout this volume; hence we will not enlarge upon the subject here.

Winter thunderstorms.—Winter thunderstorms occur in the Gulf States and along the Atlantic coast as far north as New England, but their occurrence is so infrequent that we need not discuss them. Thunderstorms may also occur occasionally in the interior in late winter or early spring with unusually low surface temperatures.

RECAPITULATION.

Thunderstorms are closely associated with LOWS passing from the upper Mississippi Valley to New England. The shape of the isobars in LOWS with thunderstorms does not seem to be material. The frequency is believed to be the greatest with ill-defined LOWS, or troughs of low pressure in which the level of the barometer is between 29.90 and 30 inches. Any depression of the barometer slightly below the general level at surrounding points, such as sometimes occurs when a high-pressure system of 30 or even 30.10 inches breaks up into two or more separate areas, with slightly lower pressure between them, is a fruitful source of thunderstorms.

A HIGH advancing eastward into a region of slightly lower pressure and much higher temperature causes thunderstorms along its eastern front.

HIGHS of 30.20 inches pressure, moving eastward over the middle Plateau and Rocky Mountain region, with lower pressure south of them are accompanied by thunderstorms along and immediately to the southward of the periphery of the HIGH.

Similarly, HIGHS moving eastward across the Great Lakes and northern New England, with a trough of low pressure to the southward are attended by thunderstorms throughout the low and indeed along the southern front of the HIGH.

HIGHS over the Atlantic, about latitude 35°, that extend to and over the continent in summer and early autumn cause thunderstorms and showers throughout the South Atlantic States, and sometimes as far west as the east Gulf States, Tennessee, and the lower Ohio Valley. Pressure in the interior should be low.

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CHAPTER X.

WEATHER AND TEMPERATURE FORECASTS, WASHINGTON DISTRICT.

[COMPRISING NEW ENGLAND, THE MIDDLE AND SOUTH ATLANTIC AND EAST GULF STATES, FLORIDA, TENNESSEE, KENTUCKY, WEST VIRGINIA, OHIO, INDIANA, AND MICHIGAN.]

By ALFRED J. HENRY, Professor of Meteorology.

Definitions..... 279
Forecast periods..... 279
Seasonal influence:
Winter..... 280
Spring and autumn..... 280
Summer..... 280
Frontier of Washington district:
The western frontier..... 281
The southern frontier..... 284
Frontier of Washington district—Con.
The eastern frontier..... 285
The northern frontier..... 285
Precipitation, unexpected occurrence of..... 287
Forecasting changes in temperature, winter..... 288
Forecasting changes in temperature, summer..... 290

DEFINITIONS.

The term "weather," as used in this chapter, refers to the state of the sky, direction and force of the wind, and the occurrence or nonoccurrence of precipitation. Temperature refers solely to the air temperatures, and is expressed by such terms as "warmer," "colder," or "no change."

FORECAST PERIODS.

Each morning forecast covers two periods of 12 hours each; each evening forecast also covers two periods, but of 24 hours each. These periods are referred to as the first and second periods, respectively. In the morning forecasts the first period begins at 8 p. m. of the date of the forecast and ends at 8 a. m. of the succeeding day. It is sometimes referred to as "to-night." The name of the day of the week is given to the second period in order to avoid ambiguity. Thus, "Fair, warmer to-night; Tuesday fair, light west winds," would be the form of a morning forecast made on Monday morning. The night forecast on Monday evening would be for the 48 hours ending at 8 p. m. Wednesday, and it would be expressed thus, "Fair

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Tuesday and Wednesday, moderate south winds." The above applies to all forecast districts of the country as well as to the Washington district.

SEASONAL INFLUENCE.

The forecaster who follows the weather maps day by day is not greatly impressed with the almost imperceptible shading of the seasons the one into the other, but the beginner must expect to acquire a working knowledge of the characteristics of the seasons. Very briefly these are as follows:

Winter, the season of maximum development of LOWS and of the greatest speed of movement and naturally the most frequent alternations from clear, cold weather to warmer, cloudy weather, with rain or snow, depending on the latitude. From the forecaster's point of view the dominating note of winter is "action," and by reason of this fact most of the literature on the subject refers to winter conditions.

Spring and autumn are both transitional seasons, the first being marked by the passage of the dominant cyclonic and anticyclonic controls, and the increasing importance of local heating, as manifest by the inauguration of convectional phenomena. The beginner in the art of forecasting will notice that in late spring the southeastward movement of western LOWS across the Rocky Mountain region and the Plains States, so characteristic of winter, practically ceases, and that there is a tendency for LOWS to advance northeastward from the eastern Rocky Mountain foothills toward the Great Lakes; that the southwest LOWS of winter are no longer in evidence, but that there is a strong tendency on the part of northern HIGHS to exert a control over the movement of LOWS and also to linger over the Great Lakes or to appear unheralded over the mouth of the St. Lawrence.

Autumn.—In autumn the pendulum begins to swing toward winter; LOWS begin their march across the country, swinging more and more to the south, with the advance of the season. Generally speaking autumn is a season of light precipitation. In the Lake region November is a month of frequent gales, exceeding in that respect all other months.

Summer is the season of inaction, the *bête noire* of the forecaster; the season when convective action is at a maximum and the forecasting of rain is most difficult. Cyclonic control of the weather is at its lowest ebb and is confined practically to the northern portion of the country. Tropical storms occasionally visit the Southern States in summer and early autumn.

The LOWS which affect the weather and temperature in the Washington district come mostly from a westerly quarter; many of them

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approach over the northern circuit and belong to the class hereinbefore described as Alberta, North and South Pacific, and Colorado.

FRONTIER OF WASHINGTON DISTRICT.

The geographic boundaries of the Washington district are shown in the frontispiece.

The district forecaster must first of all determine his frontier. By frontier is meant that geographic district which is separated from the forecast district by an interval of only 24 hours' average travel on the part of the HIGH or the LOW, as the case may be. Generally speaking the Pacific is the frontier of the western half of the country and in a less degree for the Chicago and west Gulf districts. The Washington district has a somewhat extended western frontier, but practically none on the south or east. Its western frontier on the north begins anywhere between Saskatchewan on the west and Manitoba on the east, and proceeds thence in a southwesterly direction to northern Arizona. Thus it happens that LOWS which apparently originate in the northwestern corner of the map may be kept under observation for at least one day before they reach a position whence their sphere of influence within the next 36 hours falls within the district. A LOW situated in the Province of Saskatchewan will affect northern Michigan in 24 hours and in case of rapid movement the lower Lakes region in 36 hours, particularly the temperature in the cold season. Arizona LOWS on the other hand rarely affect the weather of the district during the first period, but the precipitation in the second period may be quite extensive. In the discussion of southwest LOWS in Chapter V, page 123, the importance of determining the 24-hour movement of these LOWS was emphasized. We can but repeat the caution there given.

The western frontier.—As a rule LOWS which approach the Washington district over the northern circuit cause light precipitation in the Lake region, rarely continuing longer than 12 hours, except in the cold season, when light snow continues along the leeward shores of the Great Lakes so long as the air temperature remains at the freezing point or lower and a fair breeze continues. Whether the precipitation will be in the form of rain or snow depends, of course, on the air temperatures. The doubtful points in connection with forecasts of precipitation from northwest LOWS are (1) whether there will be precipitation of consequence, even in the Lake region, and (2) if so, how far south it will extend. When the trough of the northern LOW trails southwestward as far as the middle Mississippi Valley and pressure is below 30 inches the prospect of precipitation from, say, Indiana eastward to the Atlantic is fairly good. It may be said the prospect of precipitation increases with the sinking of

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the barometer below 30 inches, but if the temperature over the Middle Atlantic States is 5° or 10° above the normal precipitation will be slow in beginning, and may not occur at all, unless the shift of the winds from south to west is attended by a fall in temperature.

A second doubtful point is the direction that the LOWS will take; whether they will pass down the St. Lawrence Valley or southeastward from Minnesota to the Virginia Capes. In a previous part of this work (p. 96) the best indications as to the direction that a LOW will take are given. To these is added, in this special case, the fact that a southeastward movement is not probable unless pressure at Bermuda is low.

Sometimes LOWS moving along the northern circuit pass off the coast in the vicinity of Long Island and develop into severe storms along the coast, as on February 15, 1914, when the pressure in the LOW sank from 30 inches on the morning of the 15th to 29.02 inches on the Maine coast on the 17th.

Only a small percentage of LOWS have a southeastward tendency which, as above stated, appears to be controlled by pressure at Bermuda. If pressure at the latter is low, 29.90 inches or less, LOWS that may have advanced to the Great Lakes are very likely to pass off the Atlantic coast in the vicinity of Chesapeake Bay. Examples: February 28 and March 3, 1905.

The western frontier for the extreme northwestern portion of the Washington district begins, as we have seen, north of the Dakotas; it may be traced thence southwestward over the Plains States, New Mexico, and Arizona. A LOW, therefore, in the western frontier will influence the weather in some part of the Washington district, if not in the first period, then, surely in the second period; and it is remarkable how rapidly precipitation will occur ahead of some LOWS. For example, on November 5, 1911, a LOW centered in Colorado caused general rain in the Washington district in the first period up to the western border of Pennsylvania and in the second period to the Maine coast. Again, on January 9, 1916, rain fell within 24 hours at a distance 1,700 miles east of a LOW that was central in Wyoming on the morning of that date.

It is, of course, impossible, in a work of this nature, to discuss in detail the supposed causes of the rapid advance of the region of precipitation ahead of the center of the LOW; we may say in general, however, that when the pressure distribution is favorable to a rapid movement of the LOW it is good practice to carry the prediction of rainfall well ahead of the prospective location of the low center.

In the colder months LOWS in either Arizona or New Mexico with a HIGH to the northeast over the upper Great Lakes may cause precipitation in Michigan in the second period; similarly an

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Arizona or New Mexico LOW, if it should follow a more southerly course, will, under favorable conditions, cause general precipitation the second period over practically the whole of Washington District south of the Ohio and east of the Mississippi. On the other hand, LOWS may reach the far southwest and linger in that region for several days without materally influencing the weather in the Washington district. This means simply that the forecaster must be able to properly diagnose the probable movement of LOWS that occupy even the most remote portions of the frontier zone. The diagnosis becomes less difficult the nearer the LOW approaches the district. The forecaster should always bear in mind that a LOW over the Texas Panhandle or Oklahoma is quite apt to intensify after recurving toward the Lake region. In this connection see under "Southwest Lows," pages 123, 124.

Lows that appear over the Plains States of Kansas and Nebraska have a decided tendency in certain seasons of the year to move northeastward to the Great Lakes and thence down the St. Lawrence Valley. Finally, we conclude our remarks upon LOWS that approach from a westerly quarter, with the suggestion that the student systematically investigate the movement of LOWS from various situations in the western frontier under different pressure distributions that may arise; having due regard for the precepts to be found throughout this work.

A third point in connection with northern circuit LOWS requiring caution on the part of the forecaster is that whenever pressure in the Canadian Maritime Provinces is low the reaction to higher pressures which must follow seems to act as a deterrent upon a western LOW and either to block its eastward advance or to cause it to lose its seasonal intensity.

The forecaster should therefore note whether New England is occupied by a HIGH or a LOW. If pressure is low over the Canadian Maritime Provinces and New England or over the ocean in the vicinity of the Grand Banks, as it was during the greater part of March, 1915, for example, LOWS advancing from the west will, as a rule, lose their individual energy as soon as they reach New England, merging with the general low-pressure system that temporarily occupies that region.

Sometimes a circular LOW which has advanced from the Northwest to the Great Lakes with southeast winds on its front causes very little precipitation southeastward of its center. (See maps of Oct. 26–27, 1906, Feb. 24, 1905.) The following is a somewhat similar case furnished by Prof. Frankenfield:

Southwest LOWS moving north-northeast, with their centers west of Lake Michigan, will not be attended by precipitation over lower Michigan, Indiana, Ohio, and the lower Lakes generally after the LOW center reaches northern Wis-

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consin unless there is a strong HIGH through the northwest with much lower temperature.

It is perhaps a good precept in the cold season to consider a rise in temperature as inimical to precipitation during the same forecast period and the converse, viz, that other things being equal, a fall of temperature is favorable to precipitation in the same forecast period. There are, however, many exceptions to this rule.

Following are some suggestions relative to the weather of the Lake region:

Sometimes in summer a faint depression moving eastward along the northern circuit increases in energy while in the lower Lakes region or St. Lawrence Valley; a key to the development may be found in the 12-hour barometer change over the lower Lakes. The fall in pressure is sometimes scarcely perceptible on the morning map, but whenever there is a fall when a rise should be expected careful watch for a development should be made. (See weather maps of July 17, Aug. 28, Sept. 5–6, Oct. 2, 1905.)

Northeast winds in the region of the Lower Lakes, due to a low which has advanced from the south as far as the New Jersey coast, do not, as a rule, cause precipitation along the Lakes; when, however, the low approaches from the west the case is different. (See weather maps of Feb. 21–23, 1902.)

The southern frontier.—The southern frontier lies mostly over the Gulf of Mexico beyond the shore line, whence come only occasional radiograms in the hurricane season. The subject of the approach of West India cyclones is fully discussed in Chapter VIII, "High Winds."

Lows that appear along the Gulf coast in the cold season associated with HIGHS to the northeast are nearly always attended by generous precipitation, which runs far ahead of the center of the low. Thus, with a LOW over the mouth of the Mississippi and a HIGH covering the Middle Atlantic States, the normal northeastward extension of the rain area in 24 hours brings it close to the southern Pennsylvania line, and into New England in the second forecast period.

It is advisable to group LOWS of the Gulf coast with reference to their position, either west or east of the Mississippi. Thus, LOWS central over Texas may move north-northeast toward the Great Lakes via Arkansas and Missouri, or they may take a course more due northeast via the Ohio Valley. Again, a HIGH advancing eastward over Kansas and Oklahoma may cause the LOW to take what may be called the outside course, viz, eastward across the east Gulf States and then northeastward via the Carolinas to the south coast of New England. Such a grouping will doubtless show that the tendency to follow a north-northeast course is almost negligible after

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the LOW crosses the Mississippi into the State of that name, and Alabama.

In acquiring knowledge of this character one has the opportunity to note and study the exceptions to the rule, and therein lies the value of a personal study. In the experience of the writer all of the rules and precepts known to the art have their exceptions. It is the recollection of these exceptional cases that sometimes spoil what would otherwise have been good forecasts. It has been often said that one of the qualifications of a good forecaster is an excellent memory. To this the writer would add that the ability to recall general principles in forecasting is a valuable asset to a forecaster, but that recollections of some previous failure or exceptional case when the cause of the failure or the exception was not understood had best be forgotten.

Before leaving the southern frontier we remark that LOWS that reach the Gulf coast east of the mouth of the Mississippi generally move eastward to the Atlantic by way of northern Florida. Their course then will generally depend upon the pressure distribution to the northward. In defining the future course of a LOW central over Florida or the Atlantic to the eastward of that State is one of the most unsatisfactory requirements of forecast work. We have hitherto page 125, remarked on the difficulty of making a timely forecast for the Atlantic seaboard when South Atlantic LOWS develop after the morning forecast has been made.

The eastern frontier may be dismissed with the remark that lows, except of tropical origin, do not move from the ocean westward to the land, and rarely even in the last-named case. The pressure distribution over the ocean immediately to the eastward of the continent, however, appears to greatly affect the course of lows that may be advancing from the west. The writer's attention was first drawn to the matter by the deep oceanic LOW off the New England coast on February 23, 1905. A brief study made at that time and confirmed by subsequent experience leads to the belief that a deep oceanic LOW off New England has a marked tendency to retard the speed of LOWS advancing toward New England from the west, and also, as elsewhere stated, to maintain the status quo of the weather in New England and the regions adjacent thereto. Lows thus advancing seem to merge with the greater oceanic LOW, and the effect on the weather is merely to continue the current conditions. General rains or snows are not probable.

The northern frontier.—Under ordinary conditions lows do not advance southward into the district from the north, but some LOWS after reaching the mouth of the St. Lawrence slowly drift southward over Maine and pass off to sea over Nova Scotia.

The action along the northern frontier which most complicates forecasts for the northern tier of States is the southward extension

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of HIGHS that apparently advance out of the Hudson Bay country to the St. Lawrence Valley and then spread southward and westward, being attended by a pronounced lowering of the temperature as far south as the Middle Atlantic States. These HIGHS, as before stated, also serve to block the eastward advance of LOWS, especially in spring. At that season of the year the tendency of the colder continental air is equatorward and that tendency often becomes the dominating control. A second group of HIGHS likewise centered over New England, but which have wedge-shaped extensions to the southwest that project over the South Atlantic States, should receive the forecaster's special attention. These HIGHS exert a rather marked influence upon the weather in the South and Middle Atlantic States, since at times they produce northeast winds and rain over a considerable part of that region. It is the belief of the writer that when the temperature difference along the coast between Jacksonville and New York is slight, 6° or 8°, then the northeast winds will produce light rains from the Georgia coast to the Virginia Capes, and the rain, though generally light, will continue for some time. On the other hand, when the temperature differences are considerable, say more than 10°, then there will be no rain except probably along the Florida coast. References: October 1–5, 1900; October 12, December 24, 1904.

The precipitation in the cases above described is doubtless due to the northeast winds appropriate to the circulation of the HIGH. A LOW in this case is not a necessary concomitant of the HIGH, but the presence of the HIGH creates a favorable opportunity for the development of a LOW far to the southwest.

Rain on the under (southern) side of a high.—There is evidently much more than a casual relation between the northeast winds on the southern or equatorward side of a HIGH than is generally suspected. Some of the heaviest rainfalls in the southwest—Texas, Oklahoma, and eastern New Mexico—are closely associated with the southeastward movement of a well-defined HIGH from the Great Lakes to the East Gulf or South Atlantic States in connection with a poorly defined LOW in the States named. The winds in these HIGHS are continental winds and probably cooler than the winds in the LOW wherein they descend, so that it is probably a case of convectional overturning caused by the overflow of a stratum of cold air.

In connection with the above I add two notes made in 1906 and 1908, respectively:

Inclosed HIGHS—that is, HIGHS completely inclosed by an isobar—moving eastward over Tennessee are likely to produce rain along their undersides. The most important case is that which occurs when a wedge-shaped HIGH is passing off to sea over North Carolina with a LOW advancing from Texas. In

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this case rain will be general in the Gulf and South Atlantic States and the Ohio Valley. (Mar. 21, 1908, May 29, 1902.)

A HIGH moving toward the east or northeast gives at times rain or snow on its underside. A HIGH moving southeast is not so apt to make rain as one that moves east or northeast. (See weather map of Mar. 21, 1900.)

Rain in the southwest quadrant of a high.—This subject is discussed on page 137. In this place we merely give some further references to illustrative types, viz, May 6, 1904, August 19–24, 1904, December 11, 1904, and add that the phenomenon of rain in the southwest quadrant of a rapidly moving HIGH applies best to autumn, spring, and summer.

Rain precepts from clouds.—The auxiliary cloud chart that has been made for many years in the Forecast Division of the Washington Weather Bureau Office shows the kind and amount of cloud present and the direction of movement. The predictive value of the synchronous data of cloud forms and their movement is not great. In some parts of the country the movement of cirrus clouds from the southwest is an indication of rain, but unless corroborative evidence is at hand it is not safe to make a definite forecast of rain on the evidence of the clouds alone. When cirrus (ci.) change to ci.-st. or other form of upper-sheet cloud, the rain forecast can be made with greater certainty of fulfillment; consequently it is the change in form of the cirrus *or the succession of the clouds that is of the greatest moment to the forecaster.* Unfortunately, it is not often possible to wait for the change to take place, since these changes generally precede the occurrence of precipitation by only a few hours. Summarizing these remarks, it may be said: (*a*) A movement of ci. from the southwest in the lower Mississippi Valley and Texas is an indication that precipitation will occur in that region or to the northeast at a later period, 24 to 48 hours after the first appearance of the cloud; (*b*) ci. moving from the southwest over Arkansas and Oklahoma, when followed by an overcast sky of ci.-st. indicates that the rain will shortly extend into the middle Mississippi Valley; (*c*) the movement of ci. from the northwest in the southeast quadrant of a high seems to indicate that the high will increase in strength and move slowly. (See the maps of Apr. 12 and 13, 1906.)

The orientation of cirrus stripes is of some aid in making the rain forecast; thus when the direction of the striæ is northwest-southeast the probability of rain is greater than when the direction is northeast-southwest.

When precipitation unexpectedly occurs in any part of a district it should be the immediate business of the forecaster to determine, for himself at least, the cause of the precipitation; otherwise there will be a tendency to forecast too much precipitation on the ground that it has already started and is continuing, the causes being un-

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known. The same tendency occurs when within a general low-pressure system several depressions of the barometer are found with quite general precipitation around them. Such an outlook seems to call for forecasts of very general precipitation, but after working with several maps of that sort one is quite apt to take the view that only a small area of precipitation, the smaller the better, should be forecast.

In concluding our remarks on precipitation we would say that LOWS which advance along the northern circuit are not so certain to produce precipitation as are those which advance from the southwest; and, on the other hand, when a LOW comes from the southwest the weather in its rear will clear just as soon as the wind shifts to the west. This is not the case at mountain stations and along the lee shores of the Great Lakes when a LOW advances from the west or northwest. The weather clears slowly in the rear of a LOW when the temperatures are relatively high and there is no anticyclone in the west.

FORECASTING CHANGES IN TEMPERATURE (WINTER).

In Chapter VI will be found a discussion of the subject of forecasting cold waves. The fall of temperature in the cold wave is in no way different from the ordinary day-to-day temperature changes, except the amplitude of the fall is greater and it is generally accomplished very quickly.

In winter a rise or fall of 10° in 24 hours is what is technically known as a verifying change; that is, a change which should have been forecast; in spring and autumn the amount of the verifying change is 8°, and finally in summer it is but 6°. The change is determined solely from the 8 a. m. and 8 p. m. observations. (See Figs. 44–51.)

The movement of HIGHS and LOWS is the foundation upon which forecasts of temperature changes are generally based.

In winter, as a general rule, higher temperatures are caused by any movement of a LOW that draws the surface air from lower to higher latitudes or from a warm ice-free water surface to the colder land; thus in the cold season winds from the Gulf of Mexico or the Atlantic Ocean will invariably cause a rise in surface temperature over the land. There is, however, this important local exception to be noted, viz, a LOW moving northward along the Carolina and Virginia coasts will not cause a rise of temperature in the interior of North Carolina or Virginia, although it will get warmer on the coast of both States. Temperature will fall on the coast as soon as the wind shifts to the west or northwest. This exception probably means that the warm air drawn toward the center of the LOW evidently does not continue in its spiral course around the latter.

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A sharp rise in temperature in the interior regions of the Washington forecast district is caused by North Pacific LOWS of winter, especially when they follow a well-defined HIGH that has moved southeastward from the Dakotas to the South Atlantic States. When a North Pacific LOW gets as far eastward as the Dakotas, warmer for the Ohio Valley, the second forecast period should be forecast except when the intervening HIGH occupies the Mississippi Valley and is open to the north. References: January 3–7, 1901; December 8, 22, 1902; February 4–6, 1904; and January 19–22, 1906.

Following are some of the writer's precepts for Ohio for the second forecast period:

It will be warmer second period; (1), when low temperatures are reached on the front of a high (zero or lower) 24 hours previous, because the reaction will be generally as much as 10° or more, unless a strong HIGH remains to the west and north; (2), on the advance of a LOW, the center of which at the time of the forecast may be north of Montana and the HIGH over Ohio or slightly to the west; (3), with a north-south LOW that moves slowly, the center of which at the morning observation extends from Minnesota southwest to the Texas Panhandle; (4), with a HIGH central over Lake Michigan open to the north, isobars trending northwest-southeast and a large area of higher temperature in Colorado, Wyoming, and Montana; (5), with southeast winds from a high into a trough of low pressure.

It will be colder second period in Ohio:

(1) With a V-shaped depression, extending from eastern Lake Superior southwest into Nebraska, when there is a sharp rise of pressure in the northwest.

(2) With a cup-shaped LOW directly north of Ohio, a strong HIGH along the Gulf coast, and a second HIGH at Prince Albert, Saskatchewan, isobars spade-shaped to south.

(3) With a LOW north of Lake Superior, spade-shaped high in Saskatchewan.

(4) With LOW in Texas and strong HIGHS northwest and northeast. This is often a case of warmer, the first period followed by colder the second.

(5) It will be colder the second period, with a high over Montana, isobars trending northwest-southeast with only a slight depression in the region of the Upper Great Lakes.

(6) With a trough of low pressure from Lake Superior to the Texas Panhandle and a high over the plateau. (Practically the same as No. 1.)

In the above it is assumed, of course, that normal movement will continue. The writer has found it very helpful to prepare such generalizations for each group of similarly situated States in the district and to note the departures therefrom which occasionally occur. The particulars wherein individual failures occur should be carefully committed to writing, for only in this way can one eventually acquire a comprehensive view of the subject, and thus pass from the specific to the general; for example, out of rule 1 for warmer in Ohio the second forecast period has been developed the following general rule applicable to fast-moving HIGHS wherever located:

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The temperature rises rapidly in the rear of a rapidly moving HIGH, especially if the temperature fall that occurred on its front was decided. When the temperature sinks to 25° or 30° below normal it is safe to forecast warmer as soon as the crest of the HIGH passes to the eastward of a place. (Jan. 10, 1905.)

After all, this is but an expression of the fact that air temperatures continually seek a state of equilibrium or a return to normal condition.

The foregoing relates mostly to winter conditions.

TEMPERATURE CHANGES IN THE WASHINGTON DISTRICT IN SUMMER.

The greatest number of temperature changes, including temporary ones caused by thundershowers, occur in the daytime, especially in the South and Southeast. In the mountain districts a relatively large number occur at night, and in the region of the Great Lakes the division between day and night is more nearly equal than elsewhere. The eastern interior stations, like Scranton and Harrisburg, Pa., Richmond and Lynchburg, Va., etc., run parallel with respect to the number of changes, while the coast stations, such as Norfolk, Va., Wilmington, N. C., etc., have a smaller number of day changes, and the night changes are still less in number. In the South, including Georgia, the night changes are very few in number. Charlotte, N. C., should be included with Georgia, as regards night changes, and Raleigh, N. C., with Richmond, Va.

Probably the most important temperature forecasts for the Washington district that are made in summer are connected with the breaking up of a hot spell or heated term, of which we will notice first the more or less local hot spell as opposed to the general hot spell or heated term. The distinction in mind is mostly concerned with the geographic location and the duration of the heated term. The heated term of the Middle West States and the interior valleys is often prolonged and coupled with severe drought as, for example, during the summer of 1913. In the Washington district short-lived, but rather intense, heated terms occasionally arise about the first week in July under the following-named pressure conditions. High pressure, 30.10 inches, is central over the South Atlantic States, and may extend as far west as the Mississippi, but the pressure gradient from the coast westward is very weak—not more than two isobars in about 600 miles. When under these conditions a LOW moves eastward across the Lake region, for reasons well understood, surface temperatures in the Middle Atlantic States reach a relatively high value; the humidity is also high and the combination, high temperatures and high humidity, produces great discomfort. A characteristic of these short-lived heated terms is the high night temperatures experienced,

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as one may perceive by the isotherm of 80° on the morning weather map. The isotherm of 80° generally first appears over southeast Virginia and northeast North Carolina as a result, doubtless, of a fall in pressure east of the Appalachians which takes place as the northern LOW passes down the St. Lawrence Valley. This fall in pressure makes itself visible on the weather maps by producing an indentation in the isobar surrounding the south Atlantic HIGH, which at this point trends northwest-southeast from western Pennsylvania to Hatteras. In any event, there is created east of the Appalachians a sort of secondary depression which eventually becomes a trough of low pressure extending from the Virginia Capes to the mouth of the St. Lawrence. (See the map of July 3, 1903.) The isotherm of 80° in the morning map first appears in this trough and rapidly spreads northeastward to and including southern New England. If, now, a HIGH follows the northern LOW in its passage eastward across the Great Lakes, the high temperatures are quickly dissipated by cooling showers. If, however, instead of a HIGH following as above, a second LOW should immediately follow the first one, then the temperature conditions are intensified and the discomfort continues. Morning temperatures above 80° are not, however, apt to persist in the humid regions of the East longer than three or four days at the outside without local overturning taking place, which results in a temporary cooling by showers. The relief from the high temperature is brought about by the development of a HIGH in the Lake region or still farther west in conjunction with the gradual disintegration of the south Atlantic HIGH. The latter, however, gives no certain indication of its disintegration and, therefore, the forecaster must be on the lookout for the development of a western HIGH and a general shower map.

Prolonged and intense heated terms such as that of the summer of 1913 in the Middle Western States are probably due to fundamental causes in the general circulation, the nature of which we do not know. We are, therefore, unable to forecast their ending until signs of dissolution appear on the weather map. These are the disintegration of the southeastern HIGH and the development of a HIGH in the northwest.

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CHAPTER XI.

FORECASTING THE WEATHER AND TEMPERATURE, CHICAGO DISTRICT.

[COMPRISING THE STATES OF ILLINOIS, MISSOURI, WISCONSIN, MINNESOTA, IOWA, NORTH DAKOTA, SOUTH DAKOTA, NEBRASKA, KANSAS, MONTANA, AND WYOMING.]

By HENRY J. COX, Professor of Meteorology.

Geographic boundaries of the district.—The confines of the district are shown in the frontispiece. There are many types of storms (LOWS) which cause precipitation within this large area, the place of origin and direction of movement differing with each particular type. In the following paragraphs these conditions will be discussed and references given to characteristic maps of each type. The normal direction of storm movement over the forecast district is from west to east. The large majority of the LOWS take the normal course, but many are diverted from their usual track by conditions of pressure and temperature which ordinarily appear on the weather map. (See figs. 31 and 32, Ch. V.) Beyond the Divide in Montana the semi-Pacific coast type of weather is found, while generally throughout the States of Montana and Wyoming and on the eastern Rocky Mountain slope conditions of the subarid type prevail. Well-marked depressions pass over the northwestern sections frequently without precipitation. These depressions are termed "dry LOWS," and usually, even when not dry, the precipitation is rather light. Over the southeastern portion of the district the passage of disturbances is not as frequent, but the accompanying precipitation is much heavier and more extensive.

WEATHER AND TEMPERATURE FORECASTS.

In the forecasting of weather and temperature, the velocity and direction of movement of HIGHS and LOWS must be considered and also all conditions that have a bearing upon these movements. We must estimate from the weather map what the distribution of pressure will be during the period for which the forecast is being made.

The normal direction and speed of HIGHS and LOWS are shown in a general way by Bigelow's chart; but there are several well-worn

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tracks that do not appear. To Bigelow's tracks over the Chicago district we might well add a track called the "overland route," which passes slightly north of east from Colorado through Kansas and extreme northern Missouri to northern Illinois, joining near Chicago Bigelow's southwest storm track. Another frequented route is from the west Gulf region northeastward, crossing the Mississippi at Cairo, and thence to the lower lakes. The trend of movement of low pressure areas in the northern Rocky Mountain and Plateau region in the colder months is normally in a southeasterly, or at least south of east direction, because the prevailing westerlies are more or less shut off and the currents in the higher altitudes which govern or control the direction of these storms turn more to the southeast, while east of the mountains, as the altitude decreases and the prevailing westerlies become more a controlling factor, the direction of movement is more east and northeast. In the Gulf region the average direction is almost due east, and farther north it is north of east. On the other hand, the normal trend of high pressure areas in the United States is southeast.

The discussion by Bowie of the method for determining the direction and velocity of storm movement which appears in the Report of the Third Convention of Weather Bureau Officials, Weather Bureau Bulletin No. 31, has much value, and the contribution by Bowie and Weightman (Monthly Weather Bureau Supplement No. 1, 1914) furnishes additional information regarding storm tracks across the country.

Movement of lows.—A HIGH of great magnitude in front of a LOW often seems to retard the LOW's progress and sometimes even to turn it decidedly from the usual course. The influence of a HIGH, whether in front or in the rear, in crowding out a LOW depends largely upon the temperature of the HIGH, since the LOW seeks to avoid cold weather, moving rapidly if cold is in its rear, and slowly if in front. This applies to all seasons of the year. (See maps of Nov. 20–Dec. 1, 1908, and Jan. 29–31, 1914.)

When a HIGH of great magnitude is in the rear of a LOW the movement of the latter is greatly accelerated. A LOW will usually take the route where the pressure is relatively low and the temperature above normal. It would seem that in advancing, a LOW seeks warmth, avoids cold, and tends to travel in the direction of relatively low pressure, high humidity, and the area of greatest rainfall, other conditions not preventing.

When the pressure is high northeast and east of a LOW, the latter's movement will ordinarily be slow, while if there is no high pressure of any importance in front of a storm the movement will ordinarily be rapid.

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The blocking of storm movement in the Chicago district by conditions 2,000 miles or more away is sometimes apparent, nor are these obstructions always confined to areas of high pressure of considerable magnitude. Instead, the contributing cause is often a deep LOW centered over or off the north Atlantic coast; whence a steep barometric gradient extends backward across the Lake region to a HIGH over the Mississippi Valley, with winds blowing out of it toward the eastern LOW. Under such conditions a disturbance which is centered on the eastern slope of the Rockies at the same time, and which would ordinarily be expected to move eastward, is invariably turned southward and does not cause precipitation over the North Central States. Precipitation in this district will then occur only in Kansas, Missouri, and southern Illinois, as the western LOW pushes southward. (Mar. 2–3, 1914; Mar. 18–19, 1914.) When a western LOW under such circumstances is diverted from its normal course and moves southward, it usually continues in that direction until it reaches Texas, when it may recurve to the east or even to the northeast. There is usually a well-marked increase in pressure over the northern Rocky Mountains or northeastern slope following the southerly movement of the western LOW. This abnormal movement is doubtless because under such conditions the eastern LOW, with its widespread depression, moves away very slowly; in fact, so slowly that the HIGHS and LOWS to the westward are blocked off, as it were, and unless the LOW takes the abnormal course, it will have to remain practically stationary.

When HIGHS and LOWS have remained stationary for two or three days, the first indication of a change is a fall in pressure at some point, either in the trough of low pressure between the HIGHS or in one of the HIGHS. If the fall occurs in the trough or in the HIGH lying to the eastward it is certain that the stagnant conditions are giving way and a change will occur immediately, even though there is no apparent change on the "A" chart. In the case of persistent HIGHS of spring over the Great Lakes region, which retard the advance of southwest LOWS, the first indication of their moving away is a fall in pressure over the upper-middle Mississippi Valley.

If severe cold overspreads the British Northwest and the northern Rocky Mountain region or reaches southeastward over North Dakota and Minnesota, a LOW advancing from the Pacific is diverted south of its normal track and usually moves south-southeastward across the middle Rocky Mountain region to the Texas Panhandle before it turns eastward or northeastward. (Feb. 9–12, 1905; Dec. 28, 1911; Jan. 9–11, 1912.)

There seems to be a tendency in the spring for LOWS to avoid the Great Lakes region, even when they are as far east as Manitoba; doubtless because of the cold of the Lakes. Numerous instances

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have been noted where LOWS moved in a southeasterly direction, especially in the month of April, instead of taking the northern circuit across the northern lakes. Sometimes the southeasterly movement may not take them entirely clear of the Lakes, but a section of the disturbance may skirt the southern portion. A number of instances of the movement of LOWS far to the south of their normal track may be found in April, 1902, and April, 1903, and in other spring months. (Apr. 5–6, 1902; Apr. 17–19, 1902; Apr. 1–3, 1903; Apr. 10–13, 1903; Apr. 1–20, 1903; Apr. 23–25, 1903.)

While a well-marked HIGH in the rear of a LOW accelerates the movement of the latter, the LOW, when well developed, will usually advance without any HIGH of consequence in its rear; but if the LOW is of the trough form, extending southward over the Rocky Mountain region or plateau, for instance, its movement eastward will be delayed until a high appears in the rear. The deeper the trough and the farther south it extends the slower will be its movement, regardless of the geographical position.

When a LOW is centered over the middle Rockies and the barometer is falling in its front, where there is no abnormal cold, the direction of movement is usually indicated by the point of greatest 12-hour fall in pressure. If this is northeast of the center the LOW will generally move northeastward; and if southeast, the LOW will move in that direction. (Feb. 4 (p)–5, 1908; Mar. 24–25, 1914.)

If there is no distinct trough extending southward from the storm center precipitation will not extend much southeast of the center. If the trough extends southward from the center the area of precipitation will extend southeast, but it will be followed by clearing weather, as is usually the case when the disturbance moves rapidly. (Feb. 4(p)–5, 1908; Mar. 24–25, 1914.)

If the LOW moves in a southeasterly direction, the area of precipitation southward and eastward will be more extensive, the rate of movement will be slower, and the clearing up will also be slower. If the greatest 12-hour pressure fall is southeast of the storm center, over Texas and Oklahoma, for instance, this southerly route can be safely counted upon; but it is a fact that this route is often taken when the greatest 12-hour fall in pressure is coincident with the storm center or even in the rear of the center. (Apr. 27(p)–29, 1908; Dec. 4–5, 1910; Jan. 27–29, 1912; Feb. 22–23, 1914.)

When a well-marked LOW is centered over the Canadian Northwest with a broad trough extending southward over the Missouri Valley and the eastern slope of the Rockies, apparently moving eastward, and the barometer is as low as 29.70 inches in Colorado, the trough will often not move eastward, but by the next morning a well-marked LOW will be found centered over western Kansas or the Texas Pan-

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handle; especially if the greatest 12-hour pressure fall is over the middle Rockies or an adjoining section. The northern portion of the disturbance will be dissipated; the storm appearing as a redevelopment farther south. (Apr. 20 p. m., 21, 1910; Apr. 15 p. m., 16, 1914.) When a long trough reaching from northern Minnesota or western Lake Superior to the far southwest is moving eastward either rapidly or slowly and a HIGH in the rear is slight as compared with the one in front, especially if the western HIGH is hardly above 30.00 inches and the barometer is low in the southwest, a LOW will be found centered in the southwest the following morning; and if rain the preceding morning is falling in the southern portion of the trough, for instance in Kansas, Oklahoma, or Texas, the southwestern disturbance will become a general rain LOW and the weather will not clear in Missouri, Kansas, or southern Illinois. The map of September 14, 1915, is an instance of this kind, even though the greatest 12-hour rise in pressure was over the southern Plains States (.44 inch at Pueblo, Colo.). This rise would ordinarily indicate fair weather for the southwest section, but in this instance rain there was general the next day.

The southern end of a trough under such conditions seldom completes its movement eastward, even when the following HIGH is of moderate magnitude, as shown by the map of Sept. 10, 1915; but in the latter case there was no rain in the southern portion of the trough, the precipitation being confined to northern sections.

In a previous paragraph we have referred to other types of storms with the greatest 12-hour pressure fall to the south or southeast of the center and it is a fact that in practically any district with such development we should usually look for a southeasterly movement of the storm with increasing chances for precipitation.

When a LOW in winter is centered on the middle or north Pacific coast, whence it extends in a trough southeast across the Rockies to the eastern slope, frequently the eastern section of the disturbance will develop as a separate disturbance and advance eastward and northeastward, the HIGH at the same time pushing down from the northwest and advancing southward over the Dakotas. If the LOW on the Pacific is not very deep, no lower than 29.60 inches, the HIGH will probably continue its movement southward over the Plains States, but if the LOW is quite deep and the isobars in front run in a northwest and southeast direction the HIGH will not do this, but instead will move eastward across the frontier States and the Great Lakes, the movement of the HIGH eastward usually being indicated by the point of greatest 12-hour rise in pressure. (Jan. 15–16, 1896; Mar. 12–13, 1906; Jan. 24–25, 1914.) In maps of February 10–13, 1905, illustrating the type where the pressure was not very low, the

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cold was felt over this entire district, owing to the fact that the initial temperatures were already low before the HIGH appeared.[1]

A trough of low pressure extending from north to south moves eastward very slowly across the Plateau and Rocky Mountain regions, but by the time it reaches the Plains States its motion eastward is accelerated and it is still further increased as it passes across the Mississippi, except when the pressure is abnormally low in the trough, or in spring, when retarded by HIGHS over the Great Lakes region.

Lows originating in the Gulf region seldom move northeast over this district, as their direction of movement is normally eastward, but when a HIGH is present on the south Atlantic coast these LOWS often take a northeasterly course up the Ohio Valley and across the Lower Lake region. This direction of movement, however, is generally shown by the changes in pressure on the barometer change map. If a LOW is centered west of the lower Mississippi at Galveston, for instance, this northeasterly movement is always possible, but if the center of the disturbance passes as far eastward as New Orleans it will then very rarely move northeast, or northward, until after it reaches the Atlantic coast. (Feb. 9–10, 1912; Feb. 13–15, 1912.) There have been, however, movements directly northward, and these are sometimes indicated by the pressure-change chart, as in the LOW of January 30–31, 1914. The disturbance of April 14, 1914, moved directly northward, but this direction of movement was not shown by the pressure map.

Often LOWS moving from the southwest or from the Gulf region are retarded and held back by a HIGH over the Great Lakes region, and sometimes the LOWS are forced back into the southwest and even into the Gulf of Mexico. In this case the HIGHS evidently block the normal progression of the LOWS as they do the advance of LOWS from the west, as stated on page 134. (June 11–14, 1906; Mar. 20–22, 1909; July 6–8, 1909.) These HIGHS become of great magnitude over the Great Lakes in the spring; they are discussed on page 134.

In the Great Lakes region disturbances, as they approach the Lakes during the spring and early summer usually decrease in energy but increase during the autumn and winter. The isobaric surfaces are depressed over the Lakes during the spring and early summer, with a resulting inflow of air aloft, which increases the barometric pressure, while the opposite is the case in fall and winter as the air over the water is then warmer than over the land. This effect is especially noticeable in the increase in intensity of HIGHS over the Lakes in spring.

[1] The type here described is also discussed in Chap. V, under North Pacific LOWS, p. 120.

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Additional information on the subject may be found in Bulletin No. VI, Geographic Society of Chicago, "Influence of Great Lakes upon movement of high and low-pressure areas."

PRECIPITATION IN CHICAGO DISTRICT, OCCURRENCE OF.

To determine when and where precipitation will occur in the Chicago district is often a problem. There are, of course, times when LOWS move in an orderly manner across the country, accompanied by the normal weather distribution. Such conditions are shown by the common types of maps and need no discussion here.

We must realize that there is a great variation in the distribution of precipitation in this district as regards the storm centers. That precipitation occurs in advance of a LOW with clearing or fair weather following in its rear was once a generally accepted precept. However, in the Chicago district a considerable proportion of the recorded precipitation occurs on the west and north sides of a LOW or a *trough* of low pressure, when the weather to the east and southeast of the *trough* is clear, with accompanying high temperatures; and the unsettled conditions are found on the "break" and to the northwest, that is, where the temperature is falling and the winds are shifting to northerly and possibly northeasterly; in other words, on the northwest side of a *trough*, assuming that it trends northeast-southwest. Sometimes on the southeast and east sides of a *trough* partly cloudy to cloudy weather prevails, and yet the precipitation does not begin until the "break" is reached. (Sept. 18–22, 1895; May 31–June 1, 1912; Jan. 30–31, 1913; Jan. 28–29, 1914.)

Precipitation on the east and southeast sides of a LOW or of a trough is noted much less frequently in the western than in the eastern portion of the Chicago district. It frequently occurs in front of the LOW in the central valleys, while very little under such conditions is noted in the Rockies or on their eastern slope, the greater amount of precipitation in the latter sections being produced under the conditions described in the preceding paragraph on the north or northwest side of a low or of a trough.[1] The northwest LOWS are often dry and precipitation in their front during the warmer months of the year in the northwest is usually confined to thunderstorms. In northwestern LOWS whose centers are in the far north, but which move eastward across the northern frontier with troughs extending southward, there is often much doubt as to the sections lying to the east, in which precipitation will first appear. When the weather is

[1] The paper written by Prof. Johan August Udden entitled "On the Cyclonic Distribution of Rainfall" in *Augustana Library Publications* No. 4 presents an interesting study of the distribution, in the west and middle west, of precipitation with reference to the position of the LOW.

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clear, or but little cloudiness prevails in front of an easterly moving trough,[1] and the center is well to the north and the depression is shallow, the disturbance may pass over the eastern confines of this forecast district without causing precipitation, and in that case it is termed a "dry" LOW. Mar. 23–25, 1910; Oct. 6–7, 1912; Nov. 20–21, 1912; Nov. 27–28, 1912.) Regardless of how clear the weather is in advance of such a trough, one must realize that precipitation is bound to start at some place during the movement eastward. The chances of precipitation depend largely upon whether the trough extends well to the southward over the district and beyond, upon the deepness of the trough, and upon the trend of the isobars and the position of the HIGHS in front and to the rear of the depression. When the *trough* extends southwestward, as we have said before, precipitation seldom occurs in front, but is confined to the rear and to the sections on the northwest side of the trough. With the trough extending directly southward, however, conditions are more uncertain and complicated. Rarely will precipitation in front of one of these troughs begin as far west as the eastern slope of the Rockies, and often a beginning is not made until the Missouri Valley is reached and more often not until the Mississippi Valley is reached.

Sometimes precipitation follows immediately in the rear of a HIGH on its west side and far in advance of the center of the following LOW, but such precipitation is a feature of the HIGH rather than of the LOW, except in the case of thunderstorms; and it is most frequent when a HIGH has not been accompanied by clearing weather, but rather by cloudy and unsettled weather both in its front and rear. (Feb. 8–10, 1913; Apr. 3–5, 1914.)

Rain is likely to occur on the southwest side of a HIGH,[2] especially in the spring and early summer, in the southwestern portion of the Chicago district, when the HIGH the day previous is located over the Northwest and moves in a southeasterly direction across the Upper Lakes, with a trough of low barometer at the same time extending from north to south over the Rocky Mountain or Plateau region, usually from the extreme north to the extreme south. This rainfall on the southwest side of a HIGH is especially likely if rain is already falling on the southeast side of the HIGH. (May 3–5, 1911; June 28, 1911; June 21–22, 1912.) See pages 305–308 for further reference to influence of highs upon precipitation.

As stated before, whether rain falls in front of a trough of low barometer or a well-defined storm center with circular or elliptical isobars depends largely upon the trend of the isobars in front.

[1] The term "trough" as here used by the author evidently refers to the entire phenomenon of circulating winds around an area of low pressure and is, therefore, synonymous with the term LOW as elsewhere used throughout this work.—Editor.

[2] See also remarks on this subject in Chap. X, p. 286.—Editor.

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Should the isobars in front of a trough run from northeast to southwest rain does not usually fall on the east or southeast side, but as the isobars incline more and more to a north–south direction rain is more and more probable, and when they reach from northwest to southeast rain is practically certain.

Examples.

Isobars northeast–southwest.—October 14–17, 1908; March 16–17, 1912; October 13–14, 1914; April 2–3, 1913; April 22–23, 1913; January 30–31, 1913.

Isobars north–south.—April 3–5, 1910; November 30–December 1, 1912; May 1, 1912; April 25–26, 1912; October 22–23, 1913; July 1–2, 1912.

Isobars northwest–southeast.—February 11–12, 1914; May 18–19, 1913; March 2, 1912; April 7–9, 1913; May 13–14, 1913.

In some well-defined LOWS, central over eastern Colorado or western Kansas, for instance, the isobars on the southeast side run from northeast to southwest, while in the northeast quadrant they turn in a northwest direction. In such a case precipitation is quite certain in the latter quadrant, but not at all probable in the southeastern. (May 1–2, 1910; May 19–24, 1912.)

It is comparatively easy to estimate in advance the area that will be covered by precipitation in connection with an approaching low or trough when the precipitation has already started on the east side of the low, but the difficulty in the Chicago forecast district is that the disturbances are usually dry as they approach the western limits of the district, and the forecaster must face the problem of locating the sections in which rainfall will first appear. (Apr. 14–16, 1910; Jan. 5–7, 1913; Sept. 23–24, 1913.) If the pressure in the trough of the depression is as low as 29.70 inches at Omaha, it is seldom that the depression gets by the eastern Iowa stations without causing precipitation, except during dry periods. (Feb. 18–19, 1907; Jan. 25–26, 1910; Feb. 17–18, 1912; Mar. 16–17, 1912.) Should the barometer not be as low as 29.70 in southern and eastern portions of the trough, precipitation in appreciable amounts is not likely to start until Wisconsin or Illinois is reached. (May 17–18, 1912; June 3–4, 1912.) As the depression advances eastward the area of rainfall steadily extends southeastward, gradually embracing a larger area, providing the isobars in the trough have a north-south direction and the HIGH in front is in the form of a long ridge, extending from north to south. If the HIGH, however, is located well to the south and covers the South Atlantic region, the area of precipitation, instead of extending farther southeastward with the progress of the LOW, is confined rather to the Northern States, the southern boundary of the rainfall area extending farther and farther northward, provided the southeast HIGH remains stationary. If, however, the HIGH moves off the coast, the rain area will cover the Southern States.

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Generally the tendency is for the area of precipitation to spread eastward, although it sometimes spreads southeastward, sometimes northeastward, and sometimes even northward, depending upon the distribution of pressure and temperature at the time.

When there is a rapid succession of northwest LOWS, with only a slight trough extending southward, these are usually attended with but little precipitation in the Chicago district, doubtless because the atmosphere has not had time to accumulate sufficient moisture during the rapid changes. Moreover, when the LOW is shallow, there is usually less probability of precipitation than when it is deep and, when only a couple of isobars separate the HIGH in front from the LOW, the chances of precipitation are very slight. In these cases the HIGH does not extend northward over the Lakes, and the LOW takes a northerly route.

During a prolonged drought LOWS which ordinarily cause precipitation in certain sections will sometimes pass eastward without causing even cloudy weather. There is a persistency in drought conditions just as there is a persistency in rainy conditions. Rain will not be produced by an average rain type during drought, but only by a decided change. So also, during persistent and rainy conditions, precipitation occurs in connection with disturbances that, in normal periods, would not cause any precipitation whatever.

Drought conditions.—July 25–27, 1894; July 8–26, 1901; July, 1913; July 31–August 1, 1913.

Wet periods.—February 9–24, 1898; July 1–14, 1905; January 10–25, 1907; December, 1909.

When a northwest LOW is preceded by clear weather in its front, and at the same time there is some rain falling in the southwest, due possibly to its situation on the southwest side of a HIGH, or to a LOW in the far southwest, this rain will invariably extend rapidly northward through the northern LOW. For instance, we may have a dry LOW centered over Montana or Alberta, with a HIGH over the middle Western States and clear weather between the HIGH and the LOW, and some rain in Texas, Oklahoma, or perhaps Arkansas. By the next morning this rain may reach northward over the Mississippi Valley and the States lying directly west. This type is very common. (Apr. 2–4, 1910; May 14–16, 1910; Mar. 25–26, 1911; Apr. 17–18, 1911; Nov. 20, 1913.)

A modification of this type is shown on maps where an unimportant LOW is centered in the Northwest with a shallow trough, and which might be expected to pass eastward as a dry LOW, it being fair generally throughout the Northwest. But if rain is falling in the Middle States, Indiana and the Ohio Valley, for instance, although this precipitation has no connection whatever with the northwestern disturbance at the time, being due to some other unsettled

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condition, the rain area may spread westward to meet the advancing trough. The map of Sept. 17, 1915, is an instance of this type. By the morning of the 18th the rain area had spread directly westward over Iowa to the central portions of Nebraska and Kansas, and during the day spread northward to the Great Lake region, the disturbance being centered on the morning of the 18th over Lake Superior.

Another type, in which the rainfall extends eastward instead of northward or westward, is well illustrated by the maps of April 19 and 20, 1916. In this case the LOW was centered in the Middle Missouri Valley, with wide-open isobars to west and southwest. The weather in front of the LOW was clear, but precipitation was general in the Rocky Mountain region in the rear, and it spread directly eastward over the entire forecast district, including even Kansas and Missouri, which were located to the south of the center of the LOW.

When a LOW with circular isobars moves northward or northeastward over the central valleys and the southwestern portion of the Great Lakes, the movement is very slow and the weather does not clear up to the west, precipitation often continuing for days as far west as the Dakotas and Nebraska, even though the center of the disturbance may have passed east of the Chicago district. In connection with these circular LOWS unsettled conditions in the West are often so persistent that they extend into the HIGH in the rear and continue until another disturbance advances from the Pacific. Under these conditions in the wintertime it is advisable to predict a continuation of precipitation over the States on the eastern slope of the Rockies.[1] (Mar. 12–15, 1901; Jan. 28–29, 1909; Apr. 29–May 1, 1909; Oct. 24–26, 1908; Nov. 27–Dec. 1, 1910; June 16–17, 1911; Oct. 15–17, 1911.)

LOWS which originate in the Southwest,[2] of course, are usually attended by widespread precipitation, the conditions there being such that there is no doubt as to whether rain or snow will occur. The pressure changes in front of these LOWS usually show their direction of movement. A LOW which moves from Colorado eastward over the "overland route," is generally accompanied by precipitation in nearly all States of the Chicago district, on account of the favorable position of its track. Such LOWS, however, seldom cause precipitation in Kansas. In the winter and fall they usually increase in energy as they approach the Lakes (Jan. 19–21, 1895; Jan. 17–18, 1910; Nov. 16–18, 1911), while in spring they lose energy in their eastward approach (May 3–5, 1905; May 13–15, 1905; Apr. 13–16, 1912).

A LOW which moves slowly and extends as a trough of low pressure from the western Gulf region over the Central Valleys to the Lake

[1] See also the discussion of slow-moving LOWS, Ch. V, p. 101.—Editor.
[2] See also the discussion of southwest LOWS in Ch. V, p. 123.—Editor.

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region, with an area of high pressure of great magnitude in front on the Atlantic coast and another area in the rear in the Northwest, is often accompanied by heavy and protracted rains. These rains are most persistent and most prolonged when the northern end of the trough advances eastward while the southern end remains stationary. Often the trough extends in a more easterly-westerly direction, this condition producing heavy rains also. (Jan. 5–7, 1913; Feb. 26–27, 1913; Mar. 24–27, 1913.)

The weather in the rear of a fast-moving LOW in the Chicago district clears up rapidly, while in the rear of a slow-moving LOW unsettled conditions are persistent, sometimes continuing for several days. A LOW moving northeasterly is generally followed quickly by clearing weather, while one moving easterly or southeasterly is often attended by extensive precipitation on its westerly side.

When a crescent-shaped LOW of the autumn or winter type advances eastward over the Plains States, followed by a cold wave, the weather in the Chicago district in front of the crescent is generally clear, while in the rear or on the west and northwest sides snow falls. As the trough advances snow follows on the "break" or fall in temperature with the shift of the wind, but this precipitation is invariably light. While the weather in front of the trough in the Chicago district may be clear, rain may be falling farther to the southeast, in the Southern States, but this precipitation has really no connection with the western LOW. (Mar. 20–22, 1898; Nov. 20–21, 1898; Nov. 10–11, 1911.)

Aside from other conditions, the lower the pressure within a cyclonic system the slower it is in clearing; and if the pressure is abnormally low in the trough, extending southward from the storm center, the movement will be slow. (Apr. 3–5, 1910; Apr. 14–16, 1910; Dec. 21–23, 1910; Apr. 17–18, 1914.)

A rise in temperature is most pronounced on the eastern side of a LOW when the isobars run northeast and southwest, the amount of rise depending upon the gradient and the rate of translation of air from the south. As the temperature rises in front of a LOW or trough, the chances for precipitation decrease,[1] because the capacity of the air for moisture increases with rising temperature, as before stated. Naturally, with such a type, strong pressure gradients and rising temperature, the wind velocities are high; and where they are strong in the southeast quadrant and blow from south to southwest, if precipitation does occur it is brief, and clearing conditions soon follow. (Mar. 25, 1914; Apr. 10, 1914.)

In connection with the types where rain falls before the temperature has had a chance to rise, reference may be made to many maps,

[1] See also Ch. V, p. 139.—Editor.

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especially in the late spring and early summer, when rain immediately follows a HIGH, or, in other words, occurs on its west or northwest side and far in advance of the LOW. This type is different from that referred to previously, where rain falls on the southwest side of a HIGH, and it often occurs in the Missouri and Mississippi valleys on the west or northwest side of a HIGH, when the central depression is far distant in Alberta. Such rain is, in fact, a characteristic of the HIGH rather than of the LOW and seldom extends as far eastward as the western Great Lakes, but gradually clears up, with rising temperature, as the HIGHS advance. This type of rain can hardly be forecast, but the ensuing clearing conditions are better indicated. (May 16, 17, 18, 1911; June 27–30, 1911.)

Movement of highs and attendant precipitation.—While the normal direction of movement of HIGHS is southeasterly, in winter and spring they often move from the Canadian Northwest only slightly south of east across the northern frontier, with their centers over the Lake Superior region. When a HIGH is of great magnitude, the barometric level exceeding 30.75 inches, it very rarely moves from the Northwest across the northern Great Lakes, even though the pressure map may indicate such movement. If the pressure is as much as 30.80 or 30.90 inches, although the center is considerably east of the northern Rockies, it will usually advance almost directly south, often first being reinforced from the west before taking a southerly course down the eastern slope of the Rockies across Kansas and Texas. As the HIGH moves to the south it steadily loses its intensity, but there is no doubt as to its course. These HIGHS usually accompany a sweeping cold wave that later extends to the southern borders of the South Atlantic and East Gulf States and are followed in turn in the Northwest by a marked rise in temperature. This type is so common that it is not necessary to refer here to any particular maps, but additional references to it will be found in connection with the discussion of "Cold Waves."

In spring when a HIGH appears in the Canadian Northwest simultaneously with the appearance of a LOW in the South or Southwest, the HIGH generally overspreads the entire Great Lakes region as it moves eastward, but as the season advances into late May and June it is less and less likely to be felt over the southern portion of the Lake region, especially when a HIGH overlies the Southern or Southeastern States. The 12-hour pressure-change map generally indicates the direction of movement of these HIGHS, as in other types. A strong rise in pressure in the northwest and a fall over the Middle Western States, even though slight, are certain indications of a HIGH extending in its eastward movement over the southern limits of the Great Lakes and even beyond.

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In the spring months of April and May, with a HIGH in the Southeast or South and another over Manitoba and a LOW in the West near the Rockies, with an unimportant trough between the two HIGHS which extends to and across Lake Superior, as the Manitoba HIGH moves eastward with its center as far north as Lake Superior, its influence will be felt over the Great Lakes, and it will cause winds to shift to the northeast, with a decided fall in temperature at Chicago and even some distance south of that point within 24 hours. Moreover, rain will occur from southern Lake Michigan and northern Illinois westward to the Rockies, especially if rain was prevalent before on the southern side of the northwest HIGH. These HIGHS will often drift eastward and not linger over the Lakes as HIGHS usually do in the spring. (May 21–22, 1910; Apr. 30-May 2, 1910; May 24–25, 1913.)

Frequently in the spring HIGHS with clear weather in their front move from Manitoba southeast over the Lake region, bringing a decided fall in temperature without rain, but the conditions are not so well marked as those referred to in the previous paragraph. In maps of this type rain may have fallen previously in some of the Central States, as the lower Ohio and middle Mississippi valleys, for instance, but this precipitation has no connection with the HIGH and it generally ends as the HIGH approaches. (May 15–16, 1898; Apr. 12, 1914.)

In the spring a HIGH moving over the Great Lakes will often develop greatly in magnitude, because of the relatively low temperature of the air over the Lakes, the isobaric surfaces being depressed, as set forth on page 134. Sometimes these HIGHS remain for days stationary over the Lake region and frequently their influence reaches beyond to the west and south, their development being shown by rising pressure over the northern Lake region at such stations as Duluth, Marquette, and Green Bay. In forecasting the weather under such conditions the official will find the key to the solution in rising pressure and clearing weather in the northern Lake region, rather than in the observations received from the Plains States farther west. In connection with this type in forecasting for Chicago we look to the conditions at Green Bay, for instance, rather than to the reports from Davenport, Des Moines, and Omaha. (Apr. 7–9, 1900; Apr. 22–28, 1900; Mar. 20–23 1909; Apr. 22–26. 1911; Apr. 19–20, 1913; May 2–4, 1912.)

Sometimes HIGHS in spring which originate in the British Northwest, or advance from the north Pacific coast, will develop in intensity as they move southeastward across the Lake region and control the weather conditions in the eastern half of the country for nearly a week. These HIGHS, after reaching the Great Lakes, will often drift slowly southeastward across the Middle Atlantic States

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into the semi-permanent HIGH over the south Atlantic district. Frequently rain will follow over the Middle West on the southwest side of the HIGH, but if the latter takes a more southerly course after reaching the Great Lakes the rain area is not likely to advance eastward. Such HIGHS will completely break up a trough of low pressure advancing from the west. (Apr. 19–20, 1913; May 7–12, 1913; June 7–12, 1913.) These HIGHS often remain stationary over the Great Lakes and keep the rain from advancing until there is evidence of falling pressure in the sections farther west. Until the barometer begins to fall west of the Great Lakes, no matter how much rain is falling in the West, fair weather may be generally expected to continue in the Great Lakes region; moreover, in spring as a disturbance approaches from the West or Southwest, accompanied by rain, the beginning of the rain is much delayed; in fact often delayed until the storm center approaches quite closely, or until the wind shifts to southerly as the storm moves northeastward. (May 5–6, 1900; Apr. 23–26, 1905; June 1–5, 1908; May 3–6, 1910.) The reason for the persistent fair weather in the Lake region at this season is due to the influence of the HIGH, because the winds blowing out of it over a water surface are warmed considerably as they reach and pass over the land, and with the rising temperature the air has a much greater capacity for moisture. Easterly winds, at least in the spring and summer, do not indicate precipitation in the Great Lakes region, but instead, they often presage a protracted period of fair weather.

If, when a LOW or a trough of low pressure is situated in the Rocky Mountain region, or adjoining sections, a well-marked HIGH covers the Pacific coast, this HIGH will not move eastward immediately if the barometer is falling on the north Pacific coast and the winds there are from the south, but another storm will appear in that section within 12 hours.[1] In this case the movement of the trough will be retarded as in the type referred to in a preceding paragraph, unless an independent HIGH breaks off from the Pacific HIGH.

Rain seems to follow a HIGH that has produced general frosts. This is especially noticeable when the temperature rises very slowly, as the HIGH moves away, and if the trough of low pressure following extends southward.

Precipitation in the northern Rocky Mountain region from both highs and lows.—When the center of the greatest 12-hour pressure rise is over the Canadian Northwest and the barometer is falling in Montana and Wyoming, it is certain that precipitation will ensue in the Rocky Mountain region and often also on the northeastern

[1] See Chap. XII, pp. 337–338.—Editor.

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slope. Frequently during such conditions the 12-hour no-change line in pressure will pass along the northern frontier or close to it in a west-east direction. Any distribution of pressure that will cause northeast or even north winds as the HIGH moves down will bring precipitation over these sections. The weather there will clear just as soon as the winds shift to the northwest. (Feb. 25–26, 1907; Jan. 4, 1909; Feb. 14, 1910.)

We refer in this connection especially to the Rocky Mountain slope and to conditions that are most prevalent in the winter, but these same conditions in a modified degree apply to the States farther east, and even during the warmer months of the year. This is especially evident when a hot wave has prevailed over the central valleys and an area of low temperature appears in the northwest that is pushing southeastward into a trough of low pressure extending from northeast to southwest, possibly from Minnesota to the southern Rocky Mountain region or the northern part of Texas. Here the area of precipitation is entirely on the northwest side of the trough. These troughs often move slowly, especially when a HIGH of great magnitude covers the south Atlantic districts. There is not likely to be any decided eastward movement of the trough until the HIGH in the Northwest becomes at least as extensive as that over the South Atlantic. (Sept. 20–23, 1895; May 25–27, 1911.)

Precipitation should be predicted for western Montana, west of the Continental Divide, in the rainy season whenever there is precipitation and falling pressure in the North Pacific Coast States. In winter precipitation usually extends beyond the Divide and is apparent at the Helena and Yellowstone stations, so that the weather at these two places during that season may be considered to be a semi-north Pacific coast type.

Precipitation in the form of snow or sleet.—It is a matter of rather common observation, whatever the cause, that a light fall of snow will occur in winter under pressure conditions that in summer are almost invariably associated with fair weather, thus western disturbances in winter, when the temperature is considerably below freezing, often have a general area of snowfall in their front, light in amount though it be; while in warmer weather with similar pressure conditions no rain will fall. In other words, snow falls under such conditions when the barometer in the trough of the LOW may be considerably above normal. In estimating whether precipitation will or will not occur, it is necessary to determine how much the temperature is likely to rise as the depression advances, because if the temperature rises above freezing, precipitation may not be probable. During cold weather precipitation is likely to occur, therefore, with a rapidly moving depression, the movement being so rapid that sufficient time is not permitted for a considerable rise

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in temperature so that it may reach 32°. If the temperature has an opportunity to rise a few degrees in order to increase the capacity of the air for moisture, in many of these instances, especially where the snowfall amounts to only 0.1 or 0.2 inch, no precipitation will occur. To a certain extent this applies to rainfall in the warmer months, as rain is more likely when the temperature does not have the opportunity to rise much. However, with a fast moving LOW, while precipitation in winter is more likely, it is nevertheless small in amount, but in summer, with a fast moving depression, precipitation is less likely and is also small in amount, except in the case of thunderstorms.

With LOWS from the southwest during the months of November and December, rain is more likely to fall than snow in the Lake region, especially in southern portions, because the temperature of the water is still considerably above the freezing point, and as the winds blow from the water surface of the Great Lakes in a northeasterly direction during that period, it is very seldom that any considerable amount of snow falls. Snow in the southern Lake region in considerable quantities does not occur usually until the month of January is well advanced.

The question whether rain or snow will fall at any particular point during the passage of a LOW in winter depends upon the position of the place relative to the center of the LOW. The sections north and northwest of the track usually have snow while those east and southeast have rain. For instance, the precipitation in the Chicago district attending winter LOWS which pass from the southwest northeastward over the Ohio Valley usually is in the form of snow, while those which pass in the same direction over the extreme northern portions of Missouri and Illinois have precipitation mostly in the form of rain in those States, but snow in Iowa and Wisconsin.

In winter, because of the greater activity in the atmosphere and the great differences in thermal gradient, and because snow falls more easily than rain, the area of precipitation is much greater than in summer, sometimes more than three-fourths of the entire country being included within the grasp of the storm. On this account precipitation must be anticipated much further in advance of the LOW center during the colder months than in the warmer months.

Southwest LOWS that cause rain or snow over Illinois, even in large quantities at Chicago, often do not extend into Wisconsin, especially when the center of the LOW in its movement northeastward passes no farther north than the Ohio Valley. (Jan. 2–3, 1904; Jan. 30–31, 1914.)

Sleet falling in advance of a southwest LOW is almost always a sure indication that the storm will move northeast rapidly, increasing in energy, and that the sleet and snow will turn to rain along

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the track of the storm and that the precipitation will be considerable. Sleet is more likely in the central valleys and western Lake region than in other portions of the Chicago district and is usually caused by LOWS from the Gulf region moving northward or northeastward. Northwest of the track heavy snow is probable. (Feb. 3–4, 1903; Jan. 11–12, 1905; Feb. 13–14, 1909.) For further remarks on sleet, see Prof. Frankenfield's paper, Chapter IX.

When snow is falling in advance of a cold wave, it will ordinarily cease before the temperature has fallen to 10°, but in the Northwestern States snow often falls, although light, with zero temperature and even lower. Heavy snow may occur at any temperature between 20° and 32°, but is mostly likely between 24° and 30°.

In winter, after the LOW center has passed eastward, on-shore winds in the Lake region will cause a continuation of snow for a considerable distance into the interior when the wind is moderately strong; snow will fall along the lake shore to the eastward until the wind becomes light or shifts to some other direction. When snow is forecast for the western portion of the Lower Michigan Peninsula, under such conditions, it should also be forecast for northwestern Indiana, as a large and populous territory in that section has the same relative position with reference to Lake Michigan. If, however, the lake is nearly frozen over the effect of the water surface is not apparent on precipitation. For example, when Lake Superior has become almost entirely frozen, on-shore winds do not bring snow to the lake shore of upper Michigan or northern Wisconsin.

When pressure is high and temperature low over the Canadian Rockies, and a well-marked LOW lies to the south, with a steep barometric gradient, the LOW will usually move southeast and east and the HIGH will advance southeastward with northerly gales, rapidly falling temperatures, and some snow, and conditions assuming the proportions of a "blizzard" will ensue over the eastern slope of the Rockies that are especially dangerous to exposed cattle. Warnings should be issued to ranchmen well in advance. (Jan. 28–30, 1909; Mar. 13–15, 1913.)

Thunderstorms and tornadoes.—There are various types of maps which are followed by severe thunderstorms and tornadoes in the Chicago district. The low center in some cases may be over the Canadian Northwest, as that of May 25, 1896, when the Cook County, Ill., tornado occurred, while at other times the center may be farther east or southeast, over the Plains States, as in the case of the Omaha tornado, March 23, 1913. The center may often be farther east over the central valleys, as in the case of the Louisville tornado, March 27, 1890, and the St. Louis tornado, May 27, 1896.

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During thunderstorm conditions rain does not usually fall at one station in two successive periods, unless it happens to be raining at observation time. Thunderstorms are most frequent in the afternoon, but they often occur during successive nights, the intervening days being characterized by fair weather.

The "*break*" of a prolonged and general heat wave is always attended by copious rains and thunderstorms; so that when a break is impending, although conditions on the map to the west seem doubtfull, rain should be forecast.

When there is doubt as to the advance eastward of precipitation, in connection with a LOW in the west, the occurrence of thunderstorms, even though dry, is important, being an infallible sign of activity. A thunderstorm is a strong indication of unsettled conditions, whereas a sprinkle of rain without thunder or lightning may mean nothing whatever. Thunderstorm areas usually advance rapidly eastward, and often from a small beginning spread out and cover an extensive region. The thunderstorm signs should be watched closely, and rain forecast well in advance. A study of the weather maps, especially those of the thunderstorm season of 1915, will show the great value of these signs.

For further remarks on thunderstorms, see Chapter IX.

TEMPERATURE.

In the preceding paragraphs we have discussed various types of weather maps with special reference to the occurrence of precipitation; we will now consider the subject of temperature. The forecasting of temperature in the Chicago district is equally difficult because of the varied conditions of topography within this great area (see Frontispiece). However, in this district the response to pressure changes is much more direct in the case of temperature than of weather. Of course, in forecasting the endeavor is first, to estimate the probable distribution of pressure 24 and 36 hours later. Now, if these estimates are correct and we have been able to exactly determine the positions of the HIGHS and LOWS at the following observations, the predictions of temperature are certain to be practically correct. If the conditions are well marked, we can usually name the States and even the portions of the States through which the no-change line (the line separating the colder from the warmer weather) will run 36 hours later. Yet at the same time the weather forecast, i. e., the forecast as to whether precipitation will or will not occur, may fail entirely in one or several States, simply because the distribution of precipitation as regards the center of the LOW varies greatly, and the extent of the precipitation accompanying LOWS in the Chicago district even over the same routes ranges from practically nothing to a wide area.

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The mountains affect temperature as well as weather changes. The Rockies afford a natural barrier to the passage of cold waves from Alberta, and but a few cross to the western side. Often chinook winds develop on the eastern slope even when severe cold lies only a short distance to the east.

The water of the Great Lakes tempers the cold of winter and the heat of summer and exerts throughout the greater portion of the year a modifying effect upon the temperature conditions. The influence is least pronounced late in summer or autumn when the mean temperature of the air and that of the water are nearly the same.

Changes in temperature are far more numerous in the northern tier of States, the frequency gradually diminishing toward the south. Especially in the Northwestern States of the Chicago district east of the Rockies is the temperature changeable, and this is because of the proximity of that area to tracks of LOWS passing eastward over the northern circuit. On this account close attention must be paid by the forecaster to conditions on the weather map that may portend temperature changes for the Northwestern States. In the southern portion of the Chicago district, embracing Kansas, Missouri, and southern Illinois, the situation is entirely different, the changes in temperature there being relatively infrequent. It is only when conditions are pronounced that it is advisable to forecast changes in temperature for the southern portion, especially for southern Illinois.

In the following paragraphs types will be discussed illustrating the special features of temperature changes much the same as was done in the preceding paragraphs bearing upon weather and precipitation.

With the approach of a HIGH, lower temperatures may ordinarily be safely forecast for the first period for all sections east and south of the greatest 12-hour rise in pressure, and higher temperatures for the sections north and west of the pressure rise, but in forecasting for the second period the rate of progress of conditions must be very carefully estimated. If the HIGHS are moving rapidly and the changes in pressure are quite pronounced, a rise in temperature may often be expected for the second period for sections for which lower temperature is forecast for the first period.

The 12-hour pressure-change map is most important in forecasting temperature changes, whether for rises or falls, and frequently the 12-hour no-change line on the pressure map will coincide with the 24-hour no-change line on the temperature map.

It is also important to consider the departures of the temperature from normal, whether above or below, at the various stations for which forecasts are to be made. If the readings are much below the normal and the pressure change map is favorable for a rise, the changes to higher temperature will be all the more pronounced. Just

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so when the readings are above normal and the pressure-change map is favorable for a fall, so the changes to lower temperature will be pronounced.

When the temperatures are considerably above the normal, even though the pressure map indicates a still further rise, a forecast of warmer weather should be made with caution; and, on the other hand, when the temperature is much below the normal and the pressure-change map indicates a still further fall, a forecast of lower temperatures should be made with caution.[1] In these cases forecasts of stationary temperature are ordinarily more certain of verification. When, moreover, a depression in the Northwest is exceptionally deep and produces strong southerly winds, the rise in temperature is decidedly marked; and often in the winter in the Chicago district, after the temperature has already reached the normal, there is a still further rise of 20° or 30°, especially if the weather is humid and cloudy.

It should also be realized that with the advance of the seasons from winter to spring and summer there are more rises than falls, while with the approach of autumn and winter the reverse is the case.

In forecasting temperature changes it is important to take into consideration the character of the weather. Thus, the temperature will be relatively lower on a clear night than on a cloudy night and relatively higher on a clear day than on a cloudy day. See remarks on cold waves, Chapter VI.

Marked falls in temperature reaching the proportions of a cold wave are generally confined to the sections well to the eastward and southeastward of the center of the HIGH, and still farther eastward and southeastward of the greatest 12-hour rise in pressure. The only exception to this rule is the type to be mentioned under the discussion of cold waves when cloudy weather prevails in a HIGH, and it later clears, permitting considerable falls in temperature during the ensuing clear night because of free radiation. This is especially marked when the ground is snow covered and the pressure high.

A HIGH moving southeast from the far Northwest is certain to bring cold weather over the Chicago district east of the Rockies, while a HIGH moving eastward over the middle Rocky Mountain region from the Pacific coast ordinarily does not bring to the district any temperature changes of importance, unless it follows a deep depression. Then the fall in temperature is probable for the first period only. In winter a HIGH is often centered on the western Plateau for days at a time, merely spurs of little importance breaking off and following LOWS to the eastward. Occasionally this HIGH is reinforced from the north, as shown by the 12-hour rise in pressure over the Canadian Rockies, and then the complete HIGH advances eastward following a depression in its front.

[1] See remarks on reinforced HIGHS, pp. 130, 131.—Editor.

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When a HIGH moves eastward over the northern frontier and the Great Lakes region, the change to colder is not usually felt over the Plains States, except in the north portion. This type is noted repeatedly in winter, spring, and early summer.

HIGHS from the Pacific seldom move across into the Chicago district during the summer season, as they are dissipated by the heat of the interior before they can reach the Rockies. In some cases, however, they are of sufficient magnitude to make the journey, and when the barometer reaches about 29.90 inches at the Rocky Mountain stations, such as Helena and Denver, the HIGH will advance eastward over the North Central States. The HIGHS of summer which affect the Chicago district usually advance from the Canadian Northwest in a southeasterly direction, and during a heated period they will cause a "break" in a hot wave in the western Lake region and upper Mississippi Valley; while heat in the South and West will remain unbroken.

Examples of HIGHS coming across: July 4, 1913; July 7, 1913; July 16–18, 1913; Aug. 4–5, 1914.

Examples of HIGHS which did not come across: July 7–8, 1911; June 20, 1913; July 14, 1913; July 10–11, 1913.

In the spring and early summer, during the prevalence of warm weather, cooler may be forecast for the Great Lakes when the distribution of pressure is such as to indicate a "flat" map which promises lake winds over that section. Decided falls in temperature occur repeatedly at Lake stations under such conditions and often protracted periods of cool weather prevail in the spring over the Lake region because of the influence of the waters of the Lakes, when otherwise a forecaster might anticipate rising temperature. During such conditions fair weather is persistent.

When the wind blows from the Lakes, free of ice, the temperature of the air will be about that of the lake water, especially if the wind is strong. While a lake wind prevails the temperature will seldom be below freezing at any particular point, unless in a section where the ice extends far from shore, the more extensive the field of ice the less is the lake effect upon temperature. During a period when it is expected that the wind direction will continue from the lake a forecast of stationary temperature should be made for the adjacent sections. However, in autumn the influence of the Lakes on temperature is slight.

Frequently in spring and summer at Lake stations, because of an on-shore wind, the temperature is much lower than in the interior, but when the wind shifts along the lake shore and becomes a land wind, a decided rise in temperature occurs. This change may be forecast with the assistance of the pressure-change chart. If the

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barometer is falling to the north and northwest of the Lakes, the winds are quite sure to shift to the south.

When a cold HIGH is passing eastward in the winter over the central valleys, but at the same time the cold remains intense over the Northwest, including the Canadian Rockies, with unsettled weather to the south; and the isobars running northwestward over the Dakotas and eastern Montana, northeast winds and very low temperatures in the northwestern portion of the Chicago district, the temperature will not rise in the Northwest but the weather will continue cold, even though the pressure in the Canadian Northwest is falling somewhat. (Mar. 12–13, 1906; Mar. 14–15, 1906.)

If the center of the greatest 12-hour fall in pressure lies to the south it should be apparent that the pressure is rising, or soon will be, to the north or northwest, even though this is not shown by the pressure-change maps or by the 2-hour pressure changes. A change to colder weather should usually be forecast when this condition obtains.

When changes in pressure are slight and the temperatures are nearly normal, stationary temperature should be forecast.

In a previous paragraph reference has been made to the effect of a snow-covered surface on temperature. The covering serves to make both day and night temperatures relatively low under all conditions. When snow covers the ground, because of rapid radiation, minimum temperatures reach a lower degree than when the ground is bare, and in estimating the probable night minimum temperature this point must always be considered. Moreover, in the daytime, with the snow-covered surface the maximum temperature is very slow to rise above the freezing point. Doubtless the heat lost in the evaporation from the snow covering is a factor in keeping the temperature down.

When cold is brought in with a strong northwest wind and strong barometric gradient so that low temperature is likely to be reached at the beginning of the first period, a forecast of lower temperature for the second period should be made with caution. For the second period a forecast of stationary temperature should usually be made, but in cases where the conditions are moving rapidly, rising temperature should be forecast. Just so, when strong southerly winds and rising temperature prevail on the day in which the forecast is made, while one of rising temperature is ordinarily safe for the first period, it should be made with caution for the second period. In these cases the departures from normal temperatures must be given weight, as advised in a preceding paragraph.

Marked rises in temperature occur on the eastern slope of the Rocky Mountains, assuming the proportions of a "chinook" when, following a cold wave, a HIGH settles southward over the Plateau region and a LOW appears with its center on the eastern slope of the

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Canadian Rockies. If the pressure well to the south is falling and the trough deepening over eastern Wyoming and Colorado, the chinook wind will be felt to the southeastern limits of Colorado. Chinook conditions often prevail on the eastern slope when a cold HIGH covers the States lying directly to the east. (Feb., 1888; Jan. 18–21, 1897; Feb., 1905; Jan. 2–3, 1911; Jan. 12–13, 1912; Jan. 21–22, 1914.)

If during a heat wave a LOW is at some point north or northwest of Kansas, "hot winds" are probable in that State when at the same time a well-marked HIGH lies to the south or southeast, as then the gradient over Kansas is sufficiently strong to produce increasing southerly winds which cause serious damage to growing crops. This type is more or less common. (Sept. 12, 1882; June 28, 1901; July 14, 1913.)

Sometimes hot winds are general over a considerable area, embracing two or more States, while occasionally they are found in strips, doubtless due to the unequal heating of the air by soils of different character.

Ordinarily it is quite easy to forecast temperature changes for the first period, but forecasting for the second period is, of course, much more difficult on account of its being necessary to estimate what the temperature will be both at the beginning of the first period and at the end of the second. There are times, moreover, when it is difficult to estimate the temperature change 24 hours in advance, especially when a marked fall is approaching, following a rise in temperature. In such a case the reading at any particular hour will depend upon how close to that hour the cold wave will break. A great range in temperature at any given time is, of course, possible, depending upon whether the "break" will occur before or after the hour specified.

The barometer change map, especially the 12-hour change, is the best help for a forecaster in forecasting temperature changes, and this map should be used in addition to the "A"-chart. Even when a HIGH with low temperature is located over the Dakotas with a moderately steep gradient in its front, a forecaster should not hesitate when the barometer change map shows a marked fall in pressure in the northwest to forecast rising temperature for the Northwestern States and the eastern slope of the Rockies for the first period, and generally for the trans-upper Mississippi Valley for the second period. One is really safe in forecasting a rise in temperature for the first period for the sections north and west of the center of the 12-hour rise, as stated before. This should be generally an infallible rule of the forecaster. The condition is most pronounced in the recovery from a cold wave, especially when a well-marked HIGH is moving southeast. (Dec. 11–12, 1912; Apr. 8–9, 1914.)

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CHAPTER XII.

FORECASTING WEATHER AND TEMPERATURE.

NEW ORLEANS DISTRICT.

By I. M. Cline, District Forecaster.

DENVER DISTRICT.

By F. H. Brandenburg, District Forecaster.

PORTLAND (OREG.) DISTRICT.

By E. A. Beals, District Forecaster.

SAN FRANCISCO DISTRICT.

By G. H. Willson, District Forecaster.

NEW ORLEANS DISTRICT.

[Embracing the States of Arkansas, Oklahoma, Texas, and Louisiana.]

By Isaac M. Cline, District Forecaster.

Arkansas.—The most important matter for the forecaster to determine both in forecasting weather and temperature for Arkansas is the path which the center of the cyclonic disturbance will follow. When the center of the cyclonic area moves southeastward into Texas, then curves and moves toward the northeast, the duration of precipitation is longer and the temperature changes are less and extend over a longer period than when the center of the cyclonic area moves eastward to the north of Arkansas. Precipitation may be expected more frequently in the eastern than in the western portion of the State, except from March to July, inclusive, when the rainy days in the different geographical divisions of the State are nearly equal in number. Precipitation often occurs in two successive 12-hour periods and occasionally in three during the winter months, but during the summer months precipitation is not so likely to occur in two successive 12-hour periods. When the low-pressure system, either in the form of a trough or a well-defined cyclone, is over the eastern Rocky Mountain region, precipitation generally occurs

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in the winter within the next 36 hours, except in the case of what may be called "dry LOWS."

Temperature changes occur with greater uniformity in connection with similar pressure distribution than is the case with precipitation. Temperature changes are slightly more frequent in the western than in the eastern portion of the State, being most frequent over the northwestern portion. Many of the temperature changes at the p. m. observation during the summer months result from local thunderstorms and vary greatly in different years.

Oklahoma.—Precipitation occurs most frequently with LOWS which move southeastward over the Rocky Mountain region into Texas and thence to the northeastward. These LOWS, especially in winter, often give precipitation in two consecutive 12-hour periods and occasionally in three, the duration of the precipitation depending on the direction in which the LOW moves. During the summer months precipitation occurs when conditions are not so well-defined and it is a difficult matter to specifically state the 12-hour period in which precipitation will occur. There is considerable variability in the number of rain days in different years and forecasts for precipitation should be issued when conditions are moderately well-defined during wet periods and when dry periods prevail it should be forecast only when precipitation conditions are well-defined. Precipitation occurs more frequently in the extreme eastern and western portions of the State than in the central portion.

During the winter months colder must frequently be forecast for the second period in Oklahoma when the current a. m. map shows a LOW over the northern Rocky Mountain region even though a HIGH has not yet appeared within the range of reports. This condition generally gives abnormally high p. m. temperatures in Oklahoma on the current day and a sharp fall usually occurs during the afternoon of the succeeding day. The frequency of p. m. temperature changes in the summer months results from thunderstorm conditions. When conditions on the a. m. map indicate abnormally high temperatures during the p. m. of the current day lower temperatures should be forecast for the p. m. of the following day, and when abnormally low temperature is indicated for the p. m. of the current day warmer should be forecast for the p. m. of the following day.

West Texas.—No uniform precipitation types extend over this subdivision. The precipitation in west Texas is of two different types; the eastern half receives precipitation as a rule from the same conditions that give rain in the other portions of the west Gulf district—that is, from storms that develop on land and move eastward over or near the district. The rains in the western portion of this subdivision from July to October are probably caused by the LOWS moving

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eastward over the valley of the lower Colorado River, combined with a HIGH to the northward or northeastward, but not so far east as the Mississippi River.

Temperature changes exceeding the stationary limit do not occur with uniformity over this subdivision, and this makes the forecasting of temperature changes difficult, especially during the winter, when different forecasts for temperature may be required for three or four different parts of the subdivision for a 12-hour period.

East Texas.—Three-fourths of the precipitation which occurs in eastern Texas results from disturbances which have their origin on land, and the remaining fourth results mostly during the summer season from disturbances which have their origin in the Tropics or in the western portion of the Gulf of Mexico. It is well for the forecaster to bear in mind that the number of rainy days in the northeastern and southeastern portions of east Texas in the winter months is about the same, but in August and September a period of greatest frequency occurs in the southeast portion coincident with a period of least frequency over the northeastern portion. This summer period of frequency of rainy days shows at Galveston in August and September, and at Corpus Christi and Brownsville in September, and results from tropical and Gulf storms. During the summer, precipitation occurs in one locality in one period and in a neighboring locality in the following 12-hour period, therefore the exact placing of the rainfall in the forecast is difficult.

Temperature changes exceeding the stationary limit in east Texas are most frequent over the northwestern portion and are least frequent along the Gulf coast. A very noticeable fact brought out in this study is that the frequency of temperature changes in the afternoon during the summer months decreases as the Gulf coast is approached until on the Gulf coast they seldom occur. This is probably due to the fact that continuous southerly winds, in the nature of a monsoon, blowing from the Gulf of Mexico prevail during the summer months on the Texas coast and extend northward over Texas and Oklahoma with diminishing intensity; this condition apparently has such a control over temperature conditions during the summer months that on the Gulf coast, where it is most pronounced, it completely overcomes the influence of thunderstorm conditions in causing p. m. temperature changes and the effect of this monsoon wind gradually weakens as it goes northward until it completely disappears over the northwestern portion of the State. Forecasts for temperature changes in the a. m. should be issued for Texas during the summer only when conditions are pronounced and such changes are not frequent near the coast.

Louisiana.—The precipitation in Louisiana results both from disturbances which have their origin on land and those which have

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their origin in the Tropics and the Gulf of Mexico. During the fall, winter, and spring months the precipitation occurs mostly with LOWS which have their origin on land and move from west to east either across or to the north of Louisiana, and precipitation occurs with a considerable uniformity in the different geographical subdivisions of the State. From June to August, inclusive, precipitation over the northern portion of the State results from LOWS which have their origin on land and also from storms which move inland from the Gulf of Mexico, and it may be expected to occur not quite so often as once in three days. Over the southern portion of the State the precipitation in summer is more frequent and may be expected on an average once in two days during June, July, and August; the precipitation during these months is to a great extent convectional and occurs when a HIGH is centered off the south Atlantic coast with gradually diminishing intensity westward. These conditions give showers during the day, but precipitation is seldom recorded at the a. m. observation during June, July, and August unless a disturbance is moving inland from the Gulf of Mexico and similar conditions, though less marked, extend into September. The frequency of precipitation in southern Louisiana during the summer months depends on the intensity and duration of the HIGH off the south Atlantic coast. Precipitation is not quite so frequent in summer over southwestern Louisiana as it is over southeastern Louisiana.

DENVER DISTRICT.

[Comprising the States of Colorado, New Mexico, Arizona, and Utah.]

By F. H. BRANDENBURG, District Forecaster.

In dealing especially with the movement of pressure areas in the Denver forecast district, in addition to the usual problems, the forecaster has to take into account the effect of the Continental Divide, its spurs, and numerous detached ranges. Topography, therefore, adds factors that at times make the problem very complex even to one thoroughly familiar with the region. Furthermore, on the south the district borders on a region not covered by reports, while the western part at times is affected within the second period by conditions prevailing over the Pacific, of which at the time nothing more than a surmise can be had. Further, the district and adjoining territory on the west are the breeding grounds of a large proportion of the important storms that reach the Atlantic. These storms cross the central part of the country or skirt the Gulf of Mexico before moving northeastward. First in order of frequency are the northern LOWS that cross the Continental Divide far to the north. Other LOWS originating in the extreme northwest develop loops far southward,

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and when this is the case they generally divide, the primary LOWS crossing the Continental Divide in the north, where it is low, and move eastward at a normal rate, while the portions in the south generally develop into secondaries which ultimately become stronger and more important than the LOWS from which they are offshoots. The third in order of frequency, but an important class of LOWS, are those which move northward from the Gulf of California to northern Arizona and thence eastward through New Mexico or southern Colorado. These LOWS are most common during spring and the latter part of winter and are attended by heavy and general precipitation and very low temperatures on the eastern slope. Sometimes they succeed in crossing the Continental Divide. It is true that loops along the front of the depression often reach the eastern slope of the mountains, and this fact is responsible for the southward movement of high pressure along such slope. This is to be expected, even though at the time the LOW is making progress toward the eastern slope and no HIGH in a strict sense is apparent in the north. From the fact that the front of the LOW is on the eastern slope the quick development of a HIGH with attending zero weather, if in winter, may be expected in Alberta and Montana. The progress of the HIGH southward is very rapid, bringing a cold wave to the entire eastern slope of the Rocky Mountains and forming a ridge of high pressure that seems to be anchored for days until the low pressure on the western slope is filled up or forced southward into Mexico.

The weather maps of January 31, 1905, February 1–3, 1905, show the persistency of anticyclonic conditions on the northeastern slope while low pressure prevails on the west side of the Continental Divide.[1]

There is still another class of LOWS which form on the middle eastern slope, probably as a result of chinook conditions, and may be classed as secondary depressions or offshoots from a northern LOW. They do not exist long and are unimportant. (See weather maps of Jan. 14, 18, 1914; Feb. 2, 10, 1914.)

The elevated mountain masses also affect the rate of movement of HIGHS, but this influence is relatively small with most types. For that part of the district west of the Continental Divide the most important HIGHS are those which first appear on the Pacific coast. There are three types—the south Pacific, middle Pacific, and north Pacific. The first named are not ordinary HIGHS in a strict sense of the word, but are rather what is left of a high-pressure area whose northern part has been dissipated under the influence of a northern LOW, generally a V-shaped depression, extending southward to northern Arizona. In general, these HIGHS, if they move at all, move

[1] See also Chap. V, p. 120, and Chap. XI, p. 297.—Editor.

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northward to middle California and thence eastward to the middle plateau and the northern part of the southern plateau. Occasionally the HIGH, which is of no great magnitude and whose crest is not above 30.10 inches, moves eastward over Arizona. (See maps of Mar. 26 and 27, 1910; Jan. 10 and 11, 1913; and May 2 and 3, 1915.) Oftener only the front of the HIGH moves inland, the pressure not rising above 29.90, yet the effect is fully as pronounced as occurs with northern anticyclones. The front of these southwestern HIGHS, following in the wake of deep LOWS in the southern plateau and the eastern part of the middle plateau, give to the western slope high winds and sharp falls in temperature. In the colder half of the year zero temperatures usually attend the increased pressure in the northern portion of Arizona, extreme southern Utah, southwestern Colorado, and northwestern New Mexico.[1] HIGHS advancing from the Pacific, north of southern California, have successive mountain ranges to cross, and their progress is therefore relatively slow. The attending wind force and fall in temperature along their front are not nearly so marked as in the case of the southwestern HIGHS.

North Pacific HIGHS of summer, because of the heat of the interior, rarely advance inland unless their intensity and magnitude are considerable. A pressure of at least 30.30 inches seems to be necessary in order to insure the maintenance of the HIGH. In winter the interior of the country is colder than the ocean, and with the advance of the HIGHS inland there is an increase in intensity. Such HIGHS advance from British Columbia and cross the Continental Divide near the international boundary, where the barrier is low, move very rapidly, and are associated with very low temperatures in their southeastward movement, their usual track. For the most part this effect is confined to the eastern slope.

An important type of HIGHS[2] is that which usually begins to form in the middle plateau, or Great Basin, in the middle of autumn. In the beginning they are short lived. In December they are a marked feature of the weather map often for days at a time. Beginning with a moderate pressure there is built up an area of extensive high pressure, the crest often reaching 30.9 inches. These HIGHS differ from the ordinary type in that they follow up southern depressions only when reinforced by pressure fully as great over the north Pacific coast region. The persistency of these HIGHS in the Great Basin is probably primarily due to the high surrounding mountains combined with cloudless nights, which favor radiation from the snow covering on the mountain sides. These HIGHS usually remain until radiation at high levels is checked by cloudiness resulting from low

[1] See maps. Jan. 28–29, 1903; Feb. 5–6, 1904; Mar. 11–12, 1904; Mar. 23–24, 1904; Mar. 5–6, 1908; Feb. 12–13, 1911; Oct. 27–28, 1912.

[2] See Great Basin HIGHS, Chap. V, p. 132.—Editor.

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pressure approaching from the Pacific Northwest. While cold weather is the accompaniment of Great Basin HIGHS on the west side of the Continental Divide, mild weather is the attending feature on the middle eastern slope. If there is no LOW on the eastern slope one soon forms, and as it deepens the wind force increases and there is developed a foehn or chinook.

The weather map of January 3, 1906, shows the conditions preceding a chinook on the middle eastern slope; the map of the following day, January 4, shows the area affected by chinook warming to have been confined to extreme southeastern Wyoming and the plains of eastern Colorado to the Kansas line.

HIGHS that first appear north of Montana in the colder half of the year move rapidly southeastward if the pressure on the middle eastern or southeastern slope is LOW. The tendency to skirt the eastern edge of the mountains is slight when high pressure or even relatively high pressure overlies western Colorado or the adjacent regions. In the warmer half of the year Alberta HIGHS and those from the Pacific Northwest usually move eastward along the northern track, and when these HIGHS reach the Dakotas that position is favorable to the causation of thunderstorms over the middle eastern slope of the Rocky Mountains. During the latter half of summer, when the HIGH is over Nebraska and Kansas, thunderstorms may be expected on the southeastern Rocky Mountain slope.

The foregoing may be considered as a statement of conditions which actually occur, and the weather resulting therefrom, all based upon past observation, and occurring with such frequency and regularity as to justify the deduction therefrom as a basis for forecasting, of the following rules:

Northern LOWS.—Temperatures rise in the southeast quadrant with the advance of the LOW. Precipitation occurs west of the Continental Divide in front and rear of depression. On eastern slope light precipitation occurs in northern part of district with turn of pressure, and, in summer, dry thunderstorms.

Secondaries may generally be expected to form in the southern part of barometric troughs in the Middle and Northern Plateau regions and become the principal storm. A spreading of the isobars usually indicates this development.

LOWS *from the Middle Plateau* cross the Continental Divide usually in Wyoming. The time required to reach the eastern slope is much greater than in the case of northern LOWS; it may be several days or less than a day. Rapid movement may be expected when there is strong pressure moving inland from the Pacific.

LOWS *in Arizona*.—In the warmer half of the year these LOWS are northward extensions of southern LOWS; are ill-defined and may be expected to remain practically stationary. In the colder half of the

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year they are better defined, and, when not blocked, move eastward. During the period when the LOW is still in the southwest, the occurrence of easterly winds, increasing cloudiness in the west Gulf district and the beginning of precipitation therein, indicate the LOW is moving and will be deflected through Mexico.

The looping of LOWS *southward.*—During winter and spring, more often during the latter period, when the eastward movement of LOWS from the northwest is blocked by HIGHS over the upper Missouri Valley, the looping of LOWS southward along the eastern slope of the Continental Divide may be expected.

Southwestern HIGHS in winter move rapidly toward the middle plateau and cause abnormally low temperature.

Middle Pacific HIGHS following in the wake of WINTER LOWS move less rapidly than southwestern HIGHS and do not bring as low temperatures.

North Pacific HIGHS in summer, below 30.30 inches moving inland, not being able to withstand the heat of the interior may be expected to soon dissipate. In winter HIGHS from this region may be expected to increase in intensity and usually in magnitude on reaching the Rocky Mountain region. The greater cold developed is largely from radiation rather than the cold of translation.

HIGHS *from Alberta* may be expected to move rapidly along the eastern slope of the Rocky Mountains if there is a LOW in the south or even if only the front of a southwestern LOW is on the eastern slope. When, however, a LOW is forming in British Columbia or southward, the prospect that an Alberta HIGH will move southward along the eastern edge of the mountains is very remote.

Middle Plateau HIGHS may be expected to begin to form in November and to exert an important influence during December, January, and the first half of February. These areas are responsible for the chinook conditions that occur on the eastern slope when the track of LOWS is from Montana southeastward.

HIGHS *in the Dakotas and upper Mississippi Valley* in summer are attended by thunderstorms on the middle eastern slope.[1]

COLORADO.

Weather.—Few LOWS bring precipitation to the entire State. This is largely due to the fact that the trend of the high mountain ranges is north and south. Rain winds on the eastern slope are from the north and from easterly quadrants, and principally from westerly quadrants on the western slope. A stormy condition on one side of a mountain range is therefore more often than not an ideal fair weather condition for the opposite side. Nine times in ten the precipitation on the eastern slope occurs with rising pressure, the excep-

[1] See also p. 115.—Editor.

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tion being in connection with southwestern LOWS. In the eastern half of the State precipitation is to be expected with a LOW south or southwest, and thunderstorms with low and falling pressure west of the Continental Divide and high pressure northeast or east. On the western slope in winter precipitation may occur in front or in rear of a LOW, while in summer thunderstorms may be expected in or near barometric troughs.

Temperature.—The effect of the mountain ranges is fully as marked in connection with temperature as with precipitation. The temperature of west winds, independent of the mountain and valley winds, is materially modified by the topography. West of the Continental Divide winds from westerly quadrants usually bring cold weather, especially when they are high. Easterly winds are rarely strong and are usually attended by rising temperature—a mild foehn effect west of the divide when the pressure is high on the eastern slope.

On the eastern slope temperatures rise with a west wind. The ideal foehn or chinook condition is a high pressure area in western Colorado and Utah and low pressure in Montana or eastern Wyoming. The attending westerly winds are usually strong.

UTAH.

Weather.—The weather conditions of northern Utah partake of the Pacific type during practically the entire year, while in southern Utah they are of the Arizona type, especially during July and August. Precipitation occurs in the easterly quadrants of LOWS as well as in the front of HIGHS. Barometric troughs moving broadside on are usually attended by thunderstorms during July, August, and September. Clear weather attends the winter HIGH in the Great Basin, but precipitation is likely to set in over northern Utah with the breaking up of the HIGH under the influence of a northwestern LOW.

Temperature.—Temperature changes are less frequent in the plateau region than east of the Continental Divide. Sharp falls attend the passage of LOW centers, especially when the course of the LOW is southeastward. Temperatures generally rise in the southeast quadrant of north Pacific LOWS, and in the southern part of the State a rise of temperature often indicates hours in advance of its appearance the development of a LOW in the Southwest.

ARIZONA.

Weather.—The probability of the occurrence of precipitation is about twice as great in the northern part of the State as in the south-central and southeastern parts. Precipitation is relatively infrequent

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in the southwestern part of the State. The average date for the rainy season to set in is about July 7, and it generally ends before September 15. The rest of the year is generally dry, the precipitation, if any, usually occurring in February and March. Only a small proportion of LOWS is attended by precipitation. When the rainy season is fully established rain may fall without a well-defined pressure distribution, but with winds from an easterly quarter. During the rest of the year precipitation may occur with the advance from lower California of a LOW or with the development of a secondary depression in the southern quadrant of barometric troughs. The weather clears with the eastward movement of a LOW. The movement is frequently hindered by high pressure on the eastern slope of the Continental Divide. In cases where an advancing HIGH from the west does not bring a steep gradient near its front, there will be a tendency of the isobars to spread. In this event the clearing-up condition will be short lived, and another depression is more likely to form. This development is often indicated by a rise in temperature.

Temperature.—Changes in temperature are infrequent. The falls are more readily forecast than the rises, as the rises are more than likely to occur without the usual indications. In winter the east or southeast movement of a LOW is followed by sharp falls in temperature, especially in the northern part of the State. In summer a gradient from the south brings cooler weather.

NEW MEXICO.

Weather.—As in Arizona, there is a well-defined rainy season, beginning usually during the first decade of July and ending with September. During the rest of the year the occurrence of precipitation is irregular and in the southern half of the State infrequent. Conditions favorable to the occurrence of precipitation are low pressure west or southwestward of the locality and the isobars running north and south. In the rainy season the precipitation is almost entirely from thunderstorms. During the rest of the year a small amount of precipitation attends the passage of LOWS, if the movement is not very rapid. Westerly winds bring fair weather.

Temperature.—In common with other States remote from the tracks of LOWS during the greater part of the year, the variability of temperature is slight. The chinooks so common on the eastern slope in more northerly latitudes are notably absent. Marked changes to colder are more common than marked changes to warmer. As regards this feature the southeastern part of the State is perhaps an exception.

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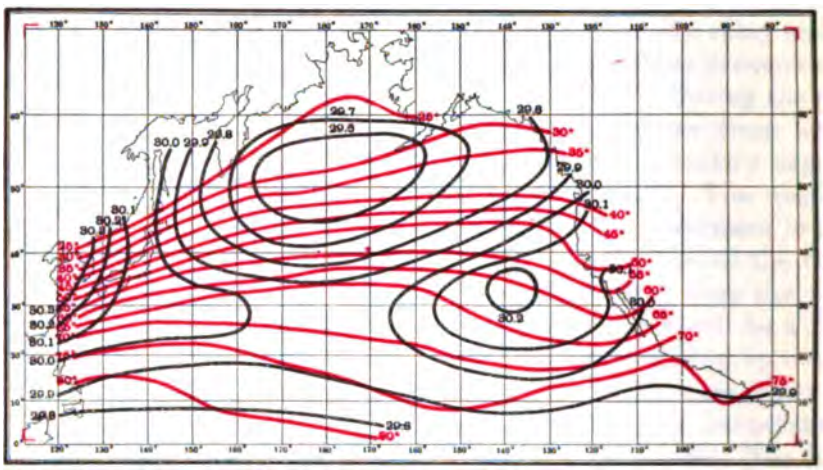

FIG. 186.—Isobars and Isotherms, North Pacific, January.

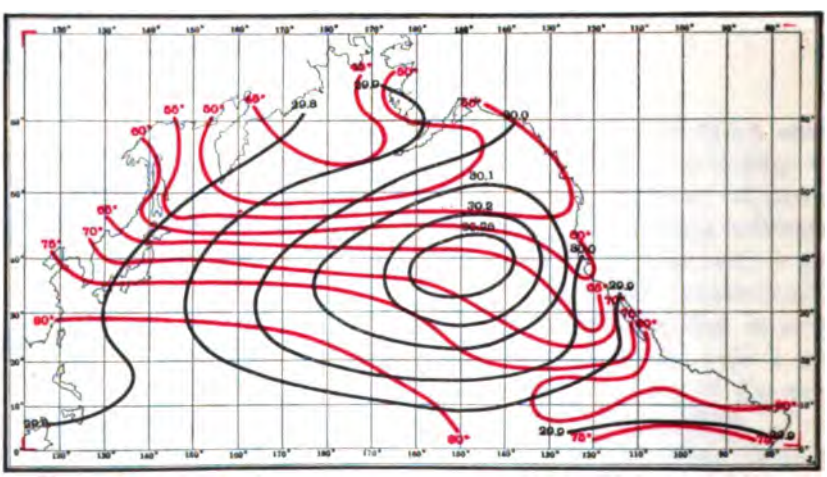

FIG. 187.—Isobars and Isotherms, North Pacific, July.

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PORTLAND, OREG., DISTRICT.

[Comprising Idaho, Washington, and Oregon.]

By E. A. Beals, *District Forecaster.*

In this forecast district probably the first striking feature attracting the attention of the novice will be the fact that the winds on many occasions do not coincide in direction or force with what is expected from the character of the pressure gradients. Under these conditions the weight to be given the different elements forecast is largely a matter of personal judgment, supported by experience.

There are two important centers of activity for the formation of LOWS and one for the formation of HIGHS that affect the weather in this district. Besides these centers of activity, HIGHS affecting the weather in the North Pacific States may originate anywhere in the interior of the British Northwest, or in northern Asia, and LOWS occasionally develop over the district itself, or so near it as to affect the weather therein.

For LOWS the most important center of activity is the semi-permanent depression overlying the extreme northern part of the Pacific Ocean. In summer there is a secondary center of activity in the great California Valley. From the former come the depressions causing our winter storms, and from the latter—often combined with LOWS from the north—come our summer rains and thunderstorms. The disturbances originating over the great California Valley are of a strictly convectional nature, probably due to the great summer heat experienced in that valley; while those from the North Pacific Ocean are probably advancing troughs of low pressure passing from the ocean to the continent. If they are of convectional origin the fact is not so apparent as it is with the California disturbances.

The principal center of activity for HIGHS is the so-called permanent belt of high pressure overlying the North Pacific Ocean near 35° north latitude. The configuration of this HIGH is such that it can hardly be called a belt of high pressure, as the isobars defining it are closed curves with oval characteristics. Figures No. 186 and No. 187, taken from insets on the Pilot Chart of the North Pacific Ocean for January and July, published by the Hydrographic Office, show the position of this HIGH during the two months in question. These charts also show the seasonal changes that take place in the LOW over the extreme northern part of the Pacific Ocean. Those forecasting the weather on the Pacific slope should have firmly fixed in their minds the changes that take place in these centers of activity from month to month, in order to recognize their offshoots when they appear on the weather map.

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The writer has no knowledge of the tracks followed by the majority of HIGHS before they affect the weather in Portland district, as they come from a region sending few if any telegraphic reports, or else originate so close to the district as to have no preceding track worth mentioning.

Having a good understanding of the above-described conditions, one is prepared to take up in detail the forecasting of weather and temperature.

After the synoptic weather charts are ready for inspection the first work is a mental calculation as to the movements that will take place in the positions of the HIGHS and LOWS during the following 24 to 48 hours. In making this calculation it is of prime importance to note the two-hour pressure changes. Quite often the information obtained from the weather charts is so evenly balanced that doubt exists as to whether fair weather or precipitation should be forecast.

After conclusions have been reached regarding the expected state of the weather comes the determination as to the expected changes in temperature. These are of relatively less importance, except during periods of extreme hot or cold weather, when they take precedence over everything else. The direction of the wind governs the case of temperature the same as for weather, and in conjunction therewith it is necessary to reach conclusions as to whether it will be clear or cloudy in the different sections of the district, as radiation plays an important part in causing changes in temperature. The temperature chart, showing departures from normal and the areas of the changes that have taken place in the preceding 24 hours, is of great assistance in placing temperature in forecasts for a district or State.

Figures 188 to 196, inclusive, show LOWS originating at the three centers of activity heretofore mentioned. Figures 188 to 191 illustrate the manner in which a LOW from California moves north over this district. The first rain was reported on the morning chart of July 9, 1913 (fig. 191), and the LOW was then central in southeastern British Columbia. Within the next 12 hours (fig. 192) the LOW had crossed the Rocky Mountains and precipitation had occurred generally in the North Pacific States, except in the arid region to the leeward of the Cascade Mountains. On the evening of July 10, 1913, the rains had practically ceased, due to the LOW having advanced eastward to Saskatchewan and a HIGH, first noted off the California coast the evening of the 8th, having advanced northward by the evening of the 10th to the mouth of the Columbia River. This HIGH the next morning, July 11, 1913 (fig. 194), was central over western Washington, and fair weather prevailed generally throughout the district.

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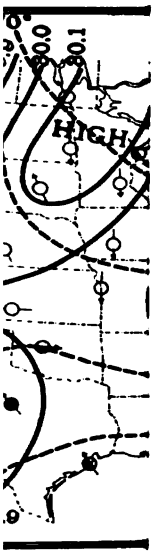
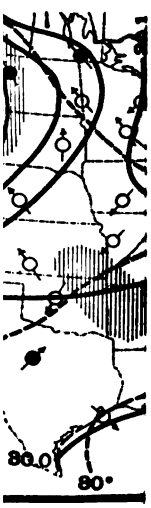


, 8 p. m., 75th



10, 1913, 8 a. 1

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Figures 195 and 196 show the first LOW of the season from the center of activity near the Aleutian Islands. Figure 195 shows when it was first observed over British Columbia and before any rain of consequence had fallen, and figure 196, 24 hours later, when the center of the disturbance was apparently over Alberta and rain had fallen in nearly all portions of the district.

My predecessor, the late B. S. Pague,[1] considered the first movement of a north Pacific HIGH from the California coast north to the Washington coast a precursor of the dry season, and, likewise, the appearance of the first LOW over northwestern Washington a precursor of the wet season on this coast, and he would announce that such was the case when these disturbances first made their appearance. The writer does not think the first appearance of these dis-

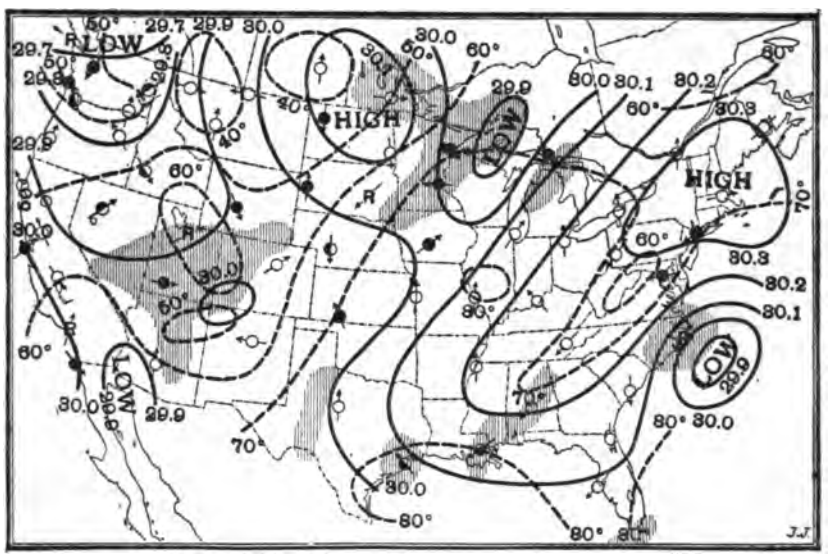

FIG. 195.—September 2, 1913. First LOW of season from north Pacific.

turbances marks a sufficiently clear distinction between the seasons to merit the attention he gave them, as sometimes the first appearance of the LOW in the northwest is followed by a long period of fair weather, and high-pressure areas from the south have moved north to the Washington coast in midwinter, and therefore are not an event marking the transition period from a wet to a dry season.

That the first appearance of these HIGHS and LOWS mark seasonal characteristics can not be denied, and although it is thought they are not of sufficient importance to warrant the making of long-range forecasts, I have prepared a table giving the dates during the five years from 1909 to 1913, inclusive, on which the first and last LOWS

[1] Weather Forecasting and Weather Types on the North Pacific Slope, pp. 6 and 7.

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from the two centers of activity appeared and the dates for the same period when the first and last HIGHS from the south moved north to the Washington coast.

TABLE 1.

	1909	1910	1911	1912	1913	Av.
First low from North Pacific Ocean	Sept. 23	Oct. 2	Sept. 14	Sept. 2	Sept. 2	Sept. 15
Last low from North Pacific Ocean	May 30	May 26	May 17	Apr. 29	Apr. 4	May 9
First low from California	Mar. 12	Mar. 13	Mar. 31	Mar. 1	Mar. 10	Mar. 13
Last low from California	Sept. 16	Oct. 11	Oct. 1	Sept. 22	Sept. 26	Sept. 27
First high from California	Mar. 9	Mar. 9	Mar. 18	Feb. 19	Feb. 18	Mar. 4
Last high from California	Oct. 16	Oct. 26	Oct. 18	Oct. 11	Oct. 2	Oct. 15

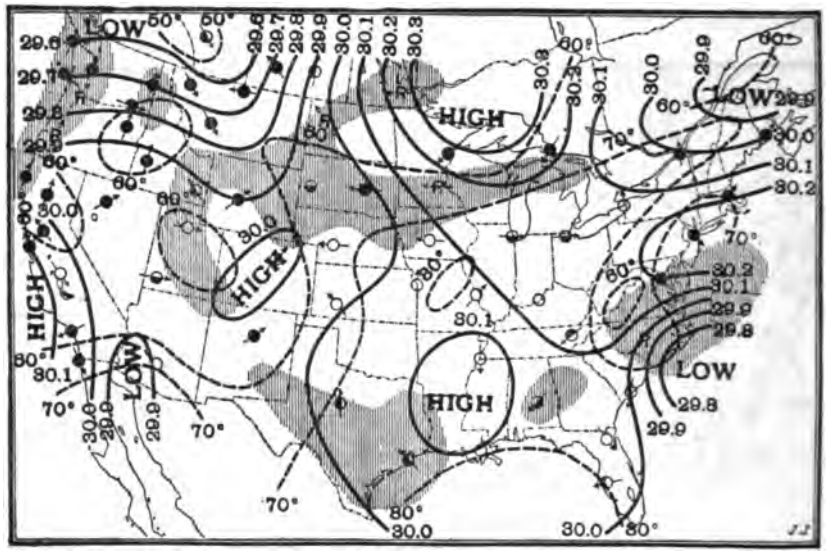

FIG. 196.—Weather map, September 3, 1913. First LOW of season from north Pacific.

It is not to be understood from the foregoing table that the dates given represent in every instance clear-cut types, for some of them are difficult of identification and different forecasters very likely would disagree in classifying the disturbances. Great pains were taken in preparing this table, but it only represents the writer's judgment in the matter.

In the case of the California disturbances nearly all the late and early ones, after streaming, as it were, northward, join forces with more or less weak LOWS from the north, none of which by itself would cause noteworthy precipitation, but when combined they usually cause general rains. The few midwinter HIGHS from the California coast which have moved north to western Washington have been excluded from the table, as otherwise there would be no seasonal distinctiveness in the phenomenon. Some of the HIGHS

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that have moved up the coast in midwinter evidently would not have gone so far north as they did if it were not for the attractive power of independent HIGHS over Alberta and eastern British Columbia. When these conditions prevail the two HIGHS unite and form one large HIGH that moves slowly southeastward and is very apt to be attended by a cold wave.

Whether a LOW moves north from California and unites with a LOW from southeastern Alaska, or a HIGH moves from the north California coast and unites with an independent HIGH over Alberta, no distinctive physical features can be detected in the disturbances after the combination has taken place, except that of greater magnitude.

The tables which follow show the percentages of temperature changes at the principal regular Weather Bureau stations in the Portland district, computed from a six-year record at the stations in Oregon and Washington and from a four-year record at the stations in Idaho for the four months—January, April, July, and October.

TABLE 2.

JANUARY.

[10° temperature changes.]

	Portland.	Seattle.	Roseburg.	Spokane.	Walla Walla.	Baker.	Boise.	Pocatello.
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
Stationary, both periods	87	87	75	77	64	75	81	65
Stationary, warmer	3	2	4	2	6	4	2	2
Stationary, cooler	3	2	6	2	6	1	2	5
Cooler, stationary	5	5	5	10	6	8	7	14
Warmer, stationary	1	3	6	6	6	7	6	10
Warmer, cooler	0	0	0	0	1	0	0	1
Cooler, warmer	0	0	1	1	0	1	0	0
Warmer, both periods	2	1	2	2	4	1	1	4
Cooler, both periods	1	0	1	0	5	3	1	0

APRIL.

[8° temperature changes.]

Stationary, both periods	48	67	42	51	46	37	33	33
Stationary, warmer	19	11	18	10	14	19	14	14
Stationary, cooler	11	8	16	14	11	13	11	7
Cooler, stationary	7	3	7	8	8	8	14	14
Warmer, stationary	3	4	5	9	11	8	13	11
Warmer, cooler	5	3	5	1	2	5	3	7
Cooler, warmer	2	2	4	2	2	4	1	3
Warmer, both periods	4	1	2	3	2	4	4	6
Cooler, both periods	1	1	1	1	4	2	1	5

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TABLE 2—Continued.

JULY.

[6° temperature changes.]

	Portland.	Seattle.	Roseburg.	Spokane.	Walla Walla.	Baker.	Boise.	Pocatello.
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
Stationary, both periods	51	57	40	39	31	33	39	33
Stationary, warmer	20	21	16	18	20	18	14	11
Stationary, cooler	15	17	16	9	12	12	11	9
Cooler, stationary	2	1	6	8	9	8	10	12
Warmer, stationary	3	2	5	8	9	9	8	14
Warmer, cooler	2	1	4	5	4	7	3	6
Cooler, warmer	3	1	7	5	3	6	1	8
Warmer, both periods	4	1	3	4	9	4	10	6
Cooler, both periods	2	1	1	4	3	3	5	2

OCTOBER.

[8° temperature changes.]

Stationary, both periods	70	72	61	62	67	55	67	54
Stationary, warmer	5	4	8	4	3	5	6	5
Stationary, cooler	9	8	8	5	5	8	9	5
Cooler, stationary	6	8	9	13	9	13	9	15
Warmer, stationary	6	8	6	11	8	11	4	11
Warmer, cooler	1	1	4	2	3	4	2	5
Cooler, warmer	0	0	1	1	0	3	0	1
Warmer, both periods	2	0	2	1	2	1	1	1
Cooler, both periods	2	1	1	1	4	1	1	3

The foregoing table illustrates how infrequently certain combinations in temperature take place, such, for instance, as cooler the first period and warmer the second period, or the reverse condition of warmer the first period and cooler the second period. In winter neither of these combinations occurs often enough to merit much consideration. This table also shows that more changes in temperature occur in the second period in summer than in winter and more occur in the first period in winter than in summer. Familiarity with the conditions as shown in the table is necessary in order to meet them intelligently in forecasting temperature, otherwise too many combinations will be placed in the forecasts.

In this district chinook or foehn[1] winds are of common occurrence at all seasons of the year. The changes in temperature that take place when these winds prevail are more pronounced in winter than they are in the summer. In summer, when the chinook or foehn winds blow, there is seldom precipitation in the mountains, and, consequently, the changes are practically adiabatic and not complicated by the addition of heat brought about by the condensation of moisture.

Figures 197 and 198 illustrate a type causing foehn winds over a large portion of the district and, consequently, a general warming up of the lower stratum of the atmosphere. These winds seldom last more than two or three days in winter. The summer foehn type

[1] See discussion in Ch. II, pp. 65, 66.—Editor.

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is different, and, while the warming process is the same, the changes in temperature are not so great and the winds are not recognized by the public as of the foehn type.

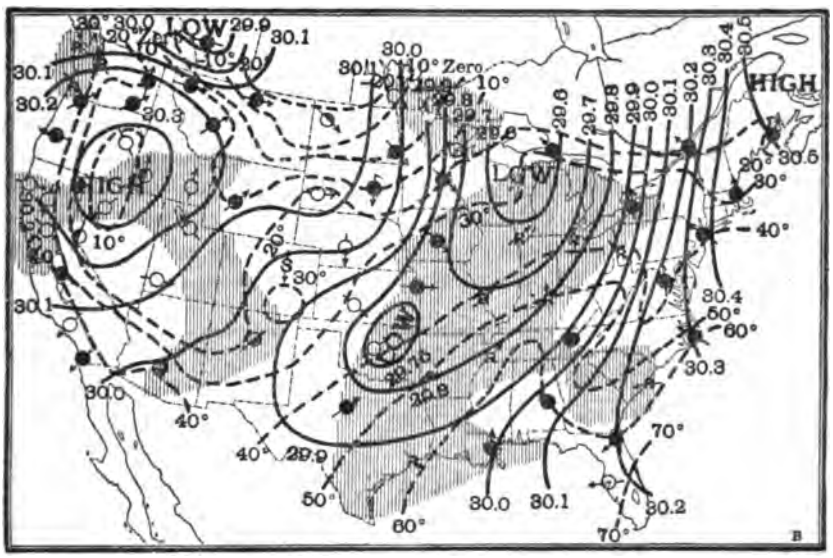

FIG. 197.—January 23, 1913. Illustrating winter chinook in Northwest; isobars in full, isotherms in broken lines; shaded areas show precipitation in last 24 hours.

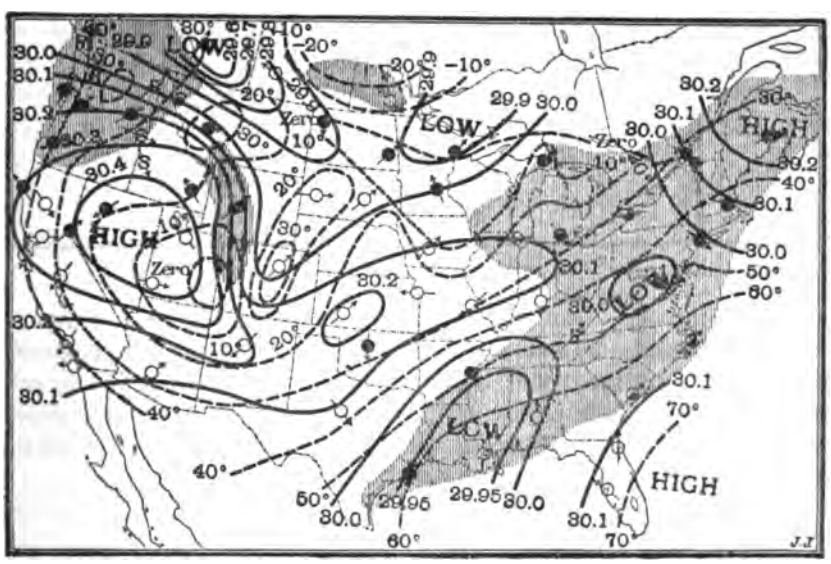

FIG. 198.—January 24, 1913. Winter chinook in Northwest.

Figure 199 is a very good illustration of the summer type of foehn winds. It will be noticed that the winter type causes the winds to move from a westerly direction and the summer type causes

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them to move from a northeasterly direction over a somewhat limited area. In the former case, the warming process is due to the air passing over the Coast and Cascade Mountains, and in the latter to its passing over the Rocky Mountains and later over the Cascade Mountains, but from the opposite direction.

The summer type of foehn winds usually causes the warmest weather of the season, and, on account of the dryness of the atmosphere, they are considered extra hazardous winds by fire patrols in forested regions. During the winter a somewhat magnified form of that type of pressure distribution which produces foehn weather in summer causes the cold waves of this district. In summer the pressure distribution, as above mentioned, produces a descent of dry air along the western slopes of the Coast and Cascade Ranges. Ac-

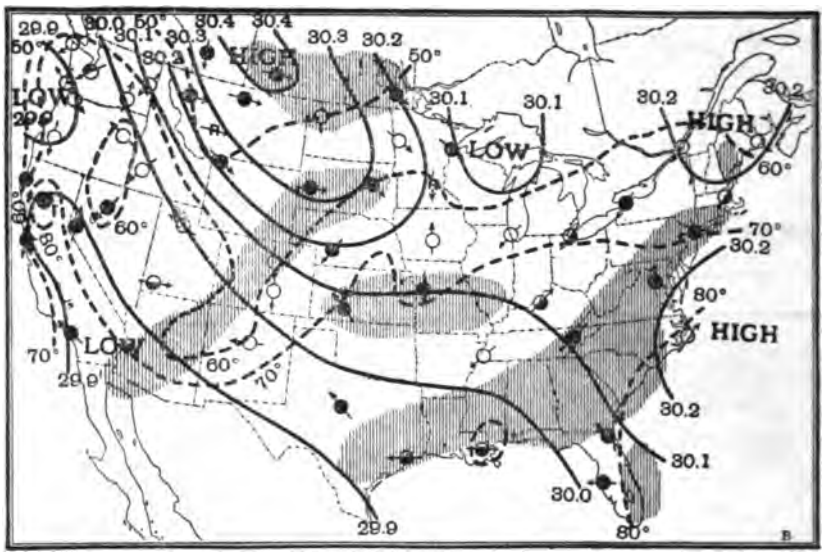

FIG. 199.—July 17, 1912. Summer chinook in Washington, Oregon, and Idaho.

cording to theory, heat is gained in the descent, the final temperatures being more or less dependent upon the initial temperatures, which, in the winter, and especially upon the occasion of a cold wave, are abnormally low. The heat gained by compression is evidently not sufficient to materially change the frigid character of the descending winds in winter.

CONCLUSIONS.

The writer feels that this paper contains very little information of value to a novice regarding the forecasting of the weather. The types used to illustrate the various phases of the work are so much better than the ordinary conditions to be found in the weather map

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that the beginner in forecasting would find them of no help on many occasions. Several years ago an attempt was made to classify by types pressure distribution causing precipitation, fair weather, and important changes in temperature. Several hundred maps were prepared and an orderly arrangement made in accordance with the class of weather that followed. It was soon found that the type of distribution causing fair weather consisted of a HIGH over western Washington and a LOW anywhere east of the Rocky Mountains. The type causing precipitation consists of a HIGH to the south, over California or Nevada, and a LOW to the north, over British Columbia, or one approaching the coast from the ocean. As the LOWS approach from the ocean and southerly winds prevail the temperature rises, and as the HIGHS approach and move across the district the temperatures fall.

In arranging the types, the greatest difficulty was experienced in getting similar ones by themselves. No two maps would be exactly alike and the difference often made it a matter of doubt as to which type the map properly belonged. After all the good types had been sorted, it was found that nearly as many remained unassorted as had been classified. These were put in classes by themselves, and thus the number of types so accumulated, with only one or two maps of each, that the task of making a simple arrangement became hopeless. Furthermore, several maps with distribution of pressure as nearly similar as it is practicable to find them, and with similar 12- and 24-hour pressure changes, were found to be followed by dissimilar weather. These maps were consulted with more or less frequency for several years, when they were finally thrown away as no longer serving a useful purpose.

SAN FRANCISCO, CAL., DISTRICT.

[Comprising California and Nevada.]

By GEORGE H. WILLSON, District Forecaster.

In 1894, when Prof. W. H. Hammon assumed charge of this forecast district, he directed me, then one of his assistants, to make practice forecasts daily, which were later verified along with the official forecasts. The practice forecasts were made entirely independent of the official ones but were always compared the morning they were made as soon as time permitted, and when differences occurred they were thoroughly discussed and reasons for the conclusions drawn were given, and the final results were noted. The object sought was to improve the forecast work in this district.

As the maps were discussed quite thoroughly each day, it soon became apparent that, while we often made the same forecast, we

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arrived at our conclusions by entirely different lines of reasoning. Nor was that all, for we found that neither had a particular method not known and used by the other, that we both recognized the same principles, and that the only difference was a matter of opinion as to which factor to give the most weight. This experience has led me to believe that no one can ever hope to successfully forecast the weather in this district by any definite set of rules.

The forecaster must not only understand the principles of cyclonic circulation and apply them to the charts he is studying, but he must also keep the topography of the country constantly in mind, and likewise the season of the year and any peculiarities prior LOWS of that season have shown. Conditions that will produce precipitation in one winter may not do so the next and those giving rain in the winter will often only bring cloudiness in the late spring or early fall. Winds that will give cold and foggy weather along the coast in the summer will produce fine, balmy weather in the winter, and the same hot wind of the summer is the cold, chilly breeze of winter.

A low temperature with the ground and vegetation wet will give a heavy frost, but it will not cause damage or make necessary protective methods like the same temperature when the ground and vegetation are dry. The former is nearly always followed by cloudiness and fog in the early morning, which allows the fruit or bud to warm gradually and prevents the strain on the tissues caused by rapidly rising temperature on a clear morning. Conditions that ordinarily would cause only moderate frosts, with little or no damage, will, if the snow extends to the lower mountains and foothills, give much colder weather and killing frosts in the orchards and vegetable fields.

The normal track of LOWS over the Pacific slope during the wet season is near the international boundary, and unless the pressure conditions are such as to deflect a LOW southward and out of the natural course, it will move east too far north to cause more than light precipitation in the extreme northern portion of this district. If the pressure is nearly normal or is falling over British Columbia and Saskatchewan as a LOW approaches the coast, it will continue moving nearly due east until passing the Rocky Mountains and there will be little or no rain south of the point where the ocean HIGH to the south of the LOW impinges on the coast. If, however, the pressure is high, or is rising with a fall in temperature over British Columbia and Saskatchewan, the storm will be deflected south, and the extent of the southerly movement will be controlled by the resistance offered by the HIGH as shown on the charts of the 12- and 24-hour pressure changes.

Sometimes a depression will move inland over the normal track and cause only cloudiness in this district, but will form a trough of

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low pressure between the Sierra Nevada and Cascade Mountains on the west and the Rockies on the east, extending south to southern California and Arizona. Then, as it moves farther east the lower end of the depression will break from the main storm and form a secondary over the southern portions of Nevada and Utah and northern Arizona, causing rain in Nevada and southern California. This is a very unsatisfactory condition to the forecaster, as the precipitation, while often heavy, is mostly confined to the mountain regions and is seldom shown at the regular Weather Bureau stations. His forecast is an official failure, but his consolation is gained from press and cooperative observers' reports. In the fall this condition often gives showers in the San Joaquin Valley during the raisin-drying season. Another type giving showers during the fall in the raisin district and in the mountains of central and southern California is the "sonora," that is, a deep depression extending northward from Mexico over the interior of California, western Arizona, and southern Nevada. These seldom give rain unless they first cause a heavy cloud-cap over the Sierra Nevada and Sierra Madre Mountains, and the rains are generally in the form of thunderstorms.

All storms on this coast move in from the Pacific; therefore it becomes necessary for the forecaster to anticipate their approach as far in advance as possible in order that warnings may be issued before the areas of high wind and rain reach the land. To accomplish this it is necessary to follow the pressure changes very closely. The writer usually bases his first rain forecast on the approach of a storm on the 2- and 12-hour barometer changes, wind direction, and increase in cloudiness, but it is seldom that all of these factors are available at that time. Sometimes it becomes necessary to make a rain forecast on only the 2-hour pressure change, at others on a change in wind direction with an increase in velocity, or on an increase in cloudiness. It would be impossible to say to which factor the most weight should be given, because the season of the year and the general characteristics of the previous LOWS of the season would have to be considered and the forecast would depend largely upon the exercise of sound judgment.

LOWS moving in from the Pacific seldom progress at a uniform rate, but rather in pulsations, and when they strike the coast often recurve back into the ocean only to return again farther north at intervals ranging from about 12 hours to 2 days. This is especially noticeable when the LOW appears south of the mouth of the Columbia River. Often when a LOW strikes the coast a portion will be detached and move eastward while the main storm remains at sea, returning as above stated, until the entire LOW has passed inland.

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After a portion of a LOW has passed inland, the pressure will rise rapidly and after a short interval of apparently clear weather it will again suddenly appear on the coast.[1] The return is usually a very rapid movement, and unless the forcaster understands this condition he will find the following day he has a "fair weather" forecast with rain falling over a large portion of the district. He should have noted that while the pressure rose rapidly and the clouds disappeared, the winds along the coast continued from the south and east, indicating a continuance of the storm in the ocean; also, that his pressure changes were too rapid, often showing a greater 12-hour change at interior stations than along the coast, and were not supported by the 24-hour changes. Never be misled by clearing weather after a depression on this coast so long as the wind remains in a southerly direction.

When a HIGH moves in from the Pacific, causing a rapid change from cloudy to clear weather, there will be a marked fall in the temperature over northeastern California and Nevada; but in the valleys and coast sections of California the changes will be much less marked, and in no section will the temperature fall be sufficient to justify a cold wave warning when the HIGH comes in from the ocean. The severe cold weather in this district appears to be a matter of air drainage, and does not occur unless there is a steep gradient to the southwestward of an area of HIGH pressure with very low temperatures moving south from British Columbia and Alberta.

In the late spring, summer, and early fall, when HIGHS cover the North Pacific States and Plateau region, light to moderate, north to east winds prevail over California, and the cool ocean influences are checked or held back. The sky is clear and insolation is great, and the air is heated dynamically in moving down the mountain slopes, causing very high temperatures in the valleys and coast sections. When these conditions are very marked they produce hot waves.

Summer fogs along the coast usually occur under three conditions: (*a*) A marked rise in the barometer on the Oregon coast extending rapidly southward will give foggy weather south of the center of the rise; (*b*) a rise in pressure on the southern coast extending north will cause foggy weather north of the center of the rise; and (*c*) when the temperature is very high in the interior and there is an inverted gradient of about 10° in 3,000 feet, as shown between San Francisco and Mount Tamalpais. The condition (*b*) during the summer months will also produce a rapid cooling in the interior, reaching Sacramento and Stockton in about 12 hours, and Red Bluff and Fresno in from 24 to 30 hours after the change at San Francisco.

[1] See, in this connection, Ch. V, p. 116.

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During the winter and early spring months a dormant HIGH central over the Plateau region will cause fog over the interior valleys extending about 1,000 or 1,500 feet up the sides of the mountains. This condition causes cold and very disagreeable weather in the valleys, while stations above the fog will experience warm sunshine and pleasant weather.

In the foregoing an attempt has been made to treat forecasting in this district on the broadest possible lines. All minor details have been purposely omitted in order to avoid lengthy explanations which might lead to confusion and would serve no good purpose in a paper of this character.

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CHAPTER XIII.

LONG RANGE WEATHER FORECASTS.

By EDWARD H. BOWIE, District Forecaster.

That there is a widespread demand by the public for weather forecasts for long periods of time, such as a coming season, or a year, is unquestionably true; that such forecasts would be of inestimable value is likewise unquestionably true; that there is not at this time, nor is it probable that there will be in the near future, a sound basis for such forecasts, is also unquestionably true. Of course exception is made in the case of forecasting of the strength and beginning of the southwest monsoons of India. Most attempts at seasonal or yearly forecasts have as a pretended basis either planetary or solar influences, the latter as manifested by sunspots; and while there may be a fairly close relationship between visible solar phenomena and the earth's weather, aside from the seasonal changes, no one may yet assume a relationship between planetary influences and the earth's weather.

In Weather Bureau Bulletin No. 35, 1904, "Long Range Weather Forecasts," the late Prof. E. B. Garriott concludes as follows:

A review of the foregoing remarks and opinions regarding the application of past and present astronomical and meteorological knowledge to the theory and practice of long-range weather forecasting leads to the following conclusions:

(1) That systems of long-range weather forecasting that depend upon planetary meteorology, moon phases, cycles, positions or movements; stellar influences or star divinations; indications afforded by observations of animals, birds, and plants; and estimates based upon the weather of certain days, months, seasons, and years have no legitimate basis.

(2) That meteorologists have made exhaustive examinations and comparisons for the purpose of associating the weather with the various phases and positions of the moon (*and the planets*) in an earnest endeavor to make advances in the science along the line of practical forecasting and have found that while the moon and perhaps the planets (to an inappreciable extent), exert some influence upon atmospheric tides, the influence is too slight and obscure to justify a consideration of lunar and planetary effects in the actual work of weather forecasting.

(3) That stars have no appreciable influence upon the weather.

(4) That animals, birds, and plants show by their condition the character of past weather, and their actions the influence of present weather and the character of weather changes that may occur within a few hours.

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(5) That the weather of days, months, seasons, and years affords no indication of future weather further than to show present abnormal conditions that the future may adjust.

(6) That six and seven day weather periods are too ill-defined and irregular to be applicable in the actual work of forecasting.

(This refers to the so-called six-seven day weather cycle. E. H. B.)

(7) That advances in the period and accuracy of weather forecasts depend upon a more exact study and understanding of atmospheric pressure over great areas and a determination of the influences, probably solar, that are responsible for normal and abnormal distributions of atmospheric pressure over the earth's surface.

(8) That meteorologists are not antagonistic to honest and well-directed efforts to solve the problem of long-range forecasting; that, on the contrary, they encourage all work in this field and condemn only those who, for notoriety or profit or through misdirected zeal and unwarranted assumptions, bring the science of meteorology into disrepute.

(9) That meteorologists appreciate the importance to the world at large of advances in the period of forecasting and are inclined to believe that the twentieth century will mark the beginning of another period in meteorological science.

These conclusions are as sound to-day as when they were written, and express the consensus of opinion of nearly all meteorologists.

The U. S. Weather Bureau has never attempted forecasts for a year, season, or a month in advance, but for several years (since 1907) it has caused to be issued forecasts for a week in advance. The character of such forecasts is shown by the following:

FORECAST FOR THE WEEK BEGINNING WEDNESDAY,

April 14, 1915.

North Atlantic States.—Generally fair weather will continue until the 18th to 20th, when the weather will become unsettled, with probably local showers. The temperature will be low during the 14th to 16th, followed by a marked change to higher temperature the latter half of the week.

Middle Atlantic States.—The weather will be fair until near the close of the week, when there will be a short period of unsettled weather and showers. The first half of the week will be cool with probably frosts; the latter part of the week will be warmer.

South Atlantic and east Gulf States.—The week will be one of generally fair weather, with temperature near the seasonal average.

West Gulf States.—Except for local showers and thunderstorms between the 16th and 18th, the week will be one of generally fair weather, with the temperatures averaging above the seasonal normal.

Ohio Valley and Tennessee.—Fair weather will prevail until the 17th–19th, when there will be local showers and thunderstorms, followed by a return of fair weather on the 20th. Temperature will rise decidedly the first half of the week and remain high thereafter until the close of the week.

Region of Great Lakes.—Fair weather will prevail during the next three or four days; the latter half of the week will be unsettled with local rains. The temperature will rise decidedly from the 14th to 16th and remain above the seasonal average the latter half of the week.

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Plains States and upper Mississippi Valley.—Generally fair weather, with temperatures above the seasonal average, will prevail until the 17th–18th, when there will be local showers and thunderstorms, to be followed by fair and cooler weather the latter part of the week.

Rocky Mountain and Plateau regions.—Local showers the beginning of the week will be followed by several days of fair weather, with temperatures near or slightly below the seasonal average.

Pacific States.—The week will be one of generally fair weather, with temperatures below the normal. Showers are probable the latter half of the week in Washington and Oregon.

Such forecasts are based on daily meteorological reports from a wide field. While it will not be possible to go into details concerning the making of such forecasts, yet a number of precepts that guide the forecaster in their preparation follow below. In addition thereto, he must constantly carry in his mind the character of the weather that is normal to the season in the several districts forecast for; he must be entirely familiar with the prevailing weather conditions of the United States and also the progress of disturbances—that is, their speed of movement and the latitude of their paths across the United States—and whether they have been attended by widespread precipitation or by only scattered areas of rain or snow. This is important, as it occasionally happens that there is a series of LOWS which cross the country nearly devoid of precipitation, whereas on other occasions, no matter how weak or ill-defined the disturbances of a series may be, all are attended by general precipitation. Hence, one of the old precepts of the forecasters of the Weather Bureau, "Watch the run of LOWS—if the tendency is toward widespread rain or snow, it is well to forecast accordingly; if, on the other hand, the LOWS have been crossing the country unattended by well-defined areas of precipitation, it is the safer course to assume that the LOW on the map under consideration will be like the one that preceded it—without precipitation of consequence." Also he must bear in mind whether current LOWS are followed by pronounced changes to colder weather or only slight reactions to normal temperature.

Having a grasp on the prevailing weather and storm types in the regions to be forecast for, the forecaster from day to day endeavors to connect them with the prevailing pressure distribution over the regions outside of the United States. From a study of the weather charts of the Northern Hemisphere the following more or less definite rules are given for the guidance of forecasters engaged in this work:

Conspicuously abnormal pressures in the regions of the so-called "centers of action" are associated with marked departures from normal conditions of weather and temperature in the United States. The centers of action that are most important in connection with the weather in the United States are the LOWS over the Aleutian

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Islands and Iceland and the HIGHS in middle latitudes of the Pacific and Atlantic Oceans and, in the winter season only, the continental HIGHS over Canada and Siberia. There seems to be a fairly well-regulated balance of this whole system, and when marked changes, whether they be of position or intensity, occur in one center of action in the majority of cases they show in the others. For instance, when the pressure level in the middle latitudes of the Atlantic for any particular month is above normal, the pressure at Iceland will probably be below normal. This is true in slightly over 80 per cent of the cases, as was brought out by Dr. J. von Hann in a study of pressures at Iceland and the Azores. A similar relation has also been observed between Hawaii and Alaska and between Hawaii and Alberta. Again, in the majority of cases, Alaska and Iceland show departures of the same sign and the same holds with respect to Hawaii and the Azores. These latter east-west relations, however, are not so well marked as the first-mentioned north-south relations. Siberia and the southern Alaska coast also show an inversion. All these centers of action exert a control of the weather in the United States, and the following statements will show in a measure just how the different centers of action operate to do this.

As almost all the LOWS which affect the weather of the United States come from the west, we naturally look to Alaska and the Pacific Ocean to ascertain the time when the LOW will first make its appearance in the United States, and also in what region it will first appear. If the Pacific Ocean HIGH is well developed and encroaches on the Pacific coast, it will be found in the great majority of cases that pressure in Alaska is below normal. Under such conditions Alberta LOWS predominate, and the first one appears about 36 hours after the pressure over Alaska has begun to fall.

If the Pacific Ocean HIGH is below normal and at the same time pressure is above normal over northern Alaska and Alberta, Pacific coast LOWS predominate rather than Alberta LOWS. For other factors that control the direction and rate of movement of the HIGHS and LOWS one must look to the eastward. The main control of direction of storm movement in the eastern portion of the United States is the HIGH over the Atlantic Ocean in the vicinity of Bermuda. When this HIGH is well developed and west of its normal position LOWS from the west will have a tendency to take courses to the northward—that is, Alberta LOWS will move along the northern border, while southwest LOWS will pass northward through the Mississippi Valley rather than take more southerly courses through the Gulf States; but if pressure in the Atlantic Ocean HIGH is below normal and its center is east of its normal position, pressure off the Middle and South Atlantic coasts will generally be below normal,

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and storms from the west will take courses well to the southward. Alberta LOWS, during the time of such pressure distribution, will pass southeastward to the middle Mississippi Valley before passing down the St. Lawrence Valley, while southwest LOWS will pass eastward through the Gulf States. With regard to the rate of storm movement, it has been noted that when there are slight variations in pressure, whether the barometer be high or low, in the main storm track, say over the British Isles, there will be a slowing down of the storm movement in the eastern United States about five or six days later, which retardation will later spread westward, provided the duration of the stagnation is sufficiently great. The storm movement in the eastern United States will not resume average progress until about five or six days after the storm movement becomes normal again over the British Isles.

In addition to the foregoing rules, the following precepts will be of help to the forecaster in arriving at an understanding of the changes in pressure over the "centers of action" and their relation to types of weather in the United States:

(1) With the pressure above normal over Alaska, LOWS appear off the Pacific coast or Plateau region and move far to the southward before recurving to New England.

(2) With high pressure over Alaska, more precipitation than usual occurs in the United States.

(3) Cold waves of more than very short duration do not occur when the barometer is LOW over Alaska, whereas intensely cold weather over the United States east of the Rocky Mountains is generally associated with high barometer over Alaska.

(4) The magnitude and position of the center of the HIGH over middle latitudes of the Atlantic Ocean has a marked influence over the weather in the eastern half of the United States and the great central valley. In the winter, precipitation above the normal and warm weather follow generally over the Eastern and Southern States when pressure is high over the Atlantic, and generally dry and cold weather follows in these regions when this ocean HIGH is below its seasonal intensity.

(5) In the winter months, with high pressure over Honolulu, HIGHS enter the United States from the Hudson Bay region or build over the St. Lawrence Valley and the Canadian Maritime Provinces.

(6) A fall in pressure at Honolulu is attended by a rise to high pressure in the Northwest. Lows will appear on the Pacific coast within three days after the fall at Honolulu.

(7) When a change to low pressure occurs at Horta, Azores, storm movements and changes in temperature accompanying and following them will be of marked intensity in the eastern half of the country.

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(8) In the summer months, if the Atlantic HIGH is well developed and pressure is high in the neighborhood of Bermuda at the same time, LOWS and changes in temperature accompanying them will be modified in intensity in the southeastern States, the character of the weather being generally fair and warm.

(9) North Pacific LOWS are offshoots from the Aleutian Islands winter LOW when the latter is well defined and somewhat south of its normal position.

(10) Alberta winter LOWS are offshoots from the Aleutian Islands LOW when it occupies a normal position, and appear over Alberta, usually within 36 hours after the pressure has begun to fall over Alaska.

(11) South Pacific LOWS occur when the Aleutian Islands LOW is far south of its normal position and there is high pressure over Alaska and the western Canadian Provinces.

(12) Marked falls in pressure over the Alaskan area are ordinarily followed by LOWS over the St. Lawrence Valley in about five days in winter and in six to seven days in summer.

(13) Marked increases in pressure over Siberia, say in the region of Irkutsk and Tomsk, will be followed in the winter by similar changes in pressure over the Canadian Northwest in about 10 days and in the summer in about 12 to 14 days or more. A large percentage of these Siberian changes are reproduced in the Canadian Northwest. The same periods hold for decreases in pressure.

(14) In the summer season, a slight shifting to the westward of the Atlantic high-pressure area gives temperatures above the normal and generally dry weather over eastern portions of the United States. If the center of this high-pressure area shifts to the westward, south of its usual position as regards latitude, the heat is general from the Gulf of Mexico to Canada. If, however, the center occupies a more northerly latitude in its western position, the heat area is confined to the more northerly districts of the United States, while the south Atlantic districts receive the benefit of the easterly winds from the ocean. (Garriott.)

(15) When the Atlantic high-pressure area occupies a position east of its normal location over the Atlantic Ocean, or exhibits pressure below normal, cool weather for the season or at least variable temperature is experienced over the eastern portions of the United States. (Garriott.)

(16) As a general proposition, the Atlantic high-pressure area controls to a great degree not only the summer weather of the greater part of the United States, but also the course and character of West Indian hurricanes. (Garriott.)

In concluding the subject attention is invited to certain types of pressure distribution in which the controlling feature apparently is

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the HIGH. The form and magnitude of the latter probably supplemented by local topographic or surface control, seem to be associated with a tendency of the prevailing weather conditions to continue for several days or a week. When these conditions of pressure distribution become firmly established the forecaster is able to take advantage of them and thus to extend the outlook generally as much as a week beyond the 36-hour period of the morning forecast.

A number of these special conditions of pressure distribution have been described in Supplement No. 1 of the Monthly Weather Review—Bowie and Weightman.

In the following paragraphs attention is directed to the indications afforded by (1) a large central HIGH, (2) Lake region HIGHS of spring, and (3) winter Plateau HIGHS.

Large central HIGHS.—An infrequent pressure distribution is that of relatively high pressure covering the interior of the United States, with minor LOWS over the Plateau and along the northern border. When this condition obtains it is persistent, and, as a rule, the crest of the HIGH drifts slowly southward, especially when the isobars trend due east and west over the southern quadrants. In such cases rain falls on the southern periphery of the HIGH and advances southward. The breaking of this pressure condition begins with the appearance of an extensive fall in pressure in the northwest, with an extension southward to Texas, where rains may already have begun. Frequently a widespread rain area follows, although the map may appear to indicate fair weather. (See maps of Jan. 1–5, 1901; Jan. 4–7, 1902; Jan. 1, 1904; Dec. 3–4, 1904.)

Lake region highs of spring.—In spring there are frequent instances where HIGHS develop over the upper Lakes and remain stationary for 36 to 48 hours or even longer. This is a fair-weather type for the Lakes and the New England and Middle Atlantic States, except that as the HIGH develops southward there is a "squeeze" (a region of opposing winds) that causes rain. If the HIGH increases, this rain area is driven south; if the HIGH drifts eastward, the rain area will follow in the region of east and northeast winds.

Winter Plateau highs.[1]—These HIGHS remain stationary, and offshoots move out of them eastward. An almost certain index to the disintegration of the Plateau HIGH may be gained from the temperature conditions prevailing within its area. Rising temperature always precedes and attends the breaking up of this HIGH. (See map of Dec. 9, 1913.) HIGHS over the western Plateau are usually coincident with fair weather, except in the Lake region, the upper Ohio Valley, and the North Atlantic States, where there is precipita-

[1] See also Great Basin HIGHS, Chs. V and XII.—Editor.

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tion due to a succession of LOWS from the Northwest. The latter statement does not hold good when the pressure is abnormally low over the north Pacific and high over the Atlantic. In this case northern LOWS are usually followed by developments in the South and Southwest.

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GLOSSARY.

TERMS RELATING TO AREAS OF LOW PRESSURE (LOWS).

Cyclone, or low.—As defined on page 75.

The term LOW on the weather map, as a rule, is synonymous with cyclone; there are occasions, however, when, strictly speaking, the use of the word LOW to indicate a cyclone is not proper. On the daily weather map the word LOW always indicates a region of low pressure, but the true cyclonic circulation may be only imperfectly developed. The use in the text follows the use on the daily weather maps. (See also Ch. I.)

Secondaries.—As defined on page 75.

Lows, well-defined, well-marked, pronounced.—These and similar expressions are to be understood as referring to the development of the LOW; particularly as regards its wind circulation, form of isobars, and, generally speaking, the level of the barometer. In each case it is to be inferred that the circulation is cyclonic and that the boundaries of the LOW are definite and sharply marked.

Lows, deep.—Defined on page 94.

V-depression.—Defined on page 75.

Troughs.—The context will generally show whether the trough of a LOW—sometimes spoken of as the trough line or a trough-shaped depression—as a whole is referred to.

Lows, intensity of.—The criterion of intensity is the steepness of the barometric gradient in some part of the circumference of the LOW. The level of the barometer is generally, though not necessarily, an index of the intensity of the LOW.

Dry lows.—Any LOW not attended by precipitation for one or more periods.

TERMS RELATING TO AREAS OF HIGH PRESSURE (HIGHS).

High.—As defined on page 75.

In the great majority of cases this term, without qualifying expression, is synonymous with anticyclone. In a small number of cases it signifies merely high pressure in which the wind circulation may depart somewhat from the true anticyclonic circulation.

High, strong, or well-defined.—When the qualifying term well-defined, or strong, is used it indicates that the true anticyclonic circulation is present; that the isobars are of elliptical form; and that the phenomenon has a progressive movement from place to place, with a definite speed (see p. 96).

Highs, ill-defined.—A poorly defined HIGH indicates one with little or no movement outflow of air, is weak, or has ceased and the pressure may be falling (see p. 96).

Pseudo highs.—The HIGHS that form as a result of reaction from low pressure while the real HIGH is yet some distance away. The pressure in pseudo HIGHS rarely reaches a level much above 30 inches.

Highs of great magnitude.—The word "magnitude" refers to geographic area; therefore a HIGH of great magnitude is one of large superficial extent. It generally happens that HIGHS of great magnitude are characterized by central pressures of relatively high level—30.50 to 30.70 inches. The primary signifi-

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cance, however, is extent of territory covered rather than a relatively high barometer level.

Highs, qualifying terms as to temperature.—It seems necessary to use at times terms descriptive of the temperature in a HIGH, with reference to its departure from the normal for the place and season; hence under temperature we have adopted the following terms:

Cold-wave highs.—A HIGH that has produced a fall in temperature in 24 hours equivalent to a technical cold wave.

Reinforced highs.—As defined on pages 130 to 131.

Cold, or cool, highs.—A HIGH with temperatures below the seasonal normal.

High of good proportions.—Same as well-defined HIGH, except that the level of the barometer may be anywhere from 30.20 to 30.50 inches in winter and 30.10 to 30.20 in summer.

BAROMETRIC GRADIENTS.

The qualifying adjectives steep, fair, moderate, or weak, when applied to pressure gradients, may be roughly interpreted in distances between consecutive tenth-inch isobars, thus:

Difference between 0.1 inch isobars (in statute miles).	Gradient.
Fifty or less	Steep.
Fifty to one hundred fifty	Fair.
One hundred fifty to three hundred	Moderate or weak.

Terms relating to temperature.—The "break," a term used to indicate the sudden change from abnormally high temperatures which occur simultaneously with the shift of the wind in a V-depression.

Blizzard.—An intensely cold, violent storm, characterized by high wind and fine, driving snow, such as those which originate on the eastern slope of the Rocky Mountains in Canada and the United States.

Flat map.—Map with very weak pressure gradients and indifferent, or neutral, pressure distribution.

Hot winds.—The winds here referred to develop over the Plains region east of the Rocky Mountains. Their chief characteristics are unusual heat and dryness and brisk movement.

Storm.—The term "storm," unless specifically qualified, may include any or all atmospheric disturbances attended by high winds, with or without rain, snow, hail, sleet, thunder, and lightning.

The term was formerly commonly employed as a synonym for cyclone, and is still occasionally used in that sense. The term as used in this work relates to the storm winds of the LOW.

"A" chart.—The chart upon which detailed weather reports are entered. The principal weather chart used by the forecaster.

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A SELECTION OF BOOKS AND PAPERS, IN ENGLISH, ON WEATHER FORECASTING.

By Miss ELEANOR BUYNITZKY.

[Prepared under the direction of C. FITZHUGH TALMAN, Professor of Meteorology, in charge of Weather Bureau Library.]

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INDEX.

Page.

Abbe, Prof. Cleveland, quoted 70, 103
Action, centers of, relation to weather in the United States 343–344
Alberta lows 120–121
Allobars, charts illustrating movement of 83
conclusions respecting 88
cycle of 83
defined 79
division of illustrated 87
formation of 80
origin of 82
position of, with respect to centers of highs and lows 81
Anallobar, defined 79
precede highs 89
relation of, to highs 86, 90
to temperature forecasts 82
Anticyclones. (*See also* Highs.)
barometer level in 130, 134, 135, 160
circulation of winds in 30
types of:
(1) permanent 60
(2) semipermanent 64
(3) migratory 64
velocity of movement of 64
wind velocity in 64, 65
Atlantic coast, fog frequency on, diagram of 265
Atlantic highs, occurrence of, in connection with thunderstorms 277
Atmosphere. (*See also* Winds.)
eastward drift of in N. Lat. 30° 99
Lake region 99
general circulation of, Chapter II 33
normal state of 33
normal drift of interrupted 101
Atmospheric motions, forces that modify 22
general principles and theory of 15

Barometer level in cyclones 94, 103, 112
anticyclones 130, 134, 135, 160
Barometric tendency, defined 79
Beals, Edward A., contributes article on cold waves in Portland, Oreg., district. 172
on frost warnings in Portland, Oreg., district 211
on forecasting weather and temperature in Portland, Oreg., district 327
Bibliography 351–358
Bigelow, Prof. (F. H.), cited 95
Blizzards, discussion of 234
definition of 351

Digitized by Google

Page.
Boise, Idaho, weather statistics for 133
Bowie, Edward H., member of board, author of Chapter VIII 217
long-range forecasts discussed, Chapter XIII 341
and Weightman (R. H.), work of cited 95
quoted 107
South Atlantic lows discussed by 126
Brandenburg, Frederick H., contributes article on cold waves in Denver district 171
on frost warnings in Denver district 209
on weather and temperature in Denver district .. 320
Bulletin T (Weather Bureau), résumé from 204–207
Buynitzky, Miss Eleanor, bibliography by 351

California, forecasting of frost in 214
Centers of action, relation of, to weather in United States 343–344
Centrifugal effects, defined 19
force, values of 24
Charts. (*See also* Weather maps.)
auxiliary pressure change 77
illustrating movement of allobars 83
pressure change 72
four-hour 225–229
temperature change 72
used in forecasting temperature changes 316
cold waves 165
Chicago district, forecasts of temperature in 311–315
weather in 299–310
Chinook, or foehn (*see also* Wind) 65
occurrences of, in Chicago district 315
Denver district 323
Washington and Oregon 332
Circular lows, movement of 100, 101
Circulation, general, of atmosphere 33
Cline, I. M., contributes paper on cold waves 170
frost warnings 208
weather and temperature forecasts, Chapter XII 317
Clouds, rain precepts from 287
Coberly (E. D.), convective rains, at New Orleans 113
Col, the (*see* Isobars) 75
Cold waves 143
charts used in forecasting of 165
duration of 165
frequency of 150
geographic distribution of 150
how they occur 149
influence of Great Lakes on 151
influence of thermometer exposure on 152
influence of topography and bodies of water on 153
loss of intensity, with movement to southeast 159
movement of 154–155
as influenced by trend of isobars 160
special conditions affecting 162

Digitized by Google

Page.
Cold waves, number of 148
occurrence of, in Denver district 171
at Modena, Utah 154
in New England 169
North Pacific district 172
Plateau region 154
South Pacific district 174
West Gulf district 170
at Winnemucca, Nev 154
types of 156–159
zones, from March to November 43
from December to February 43
Colorado, or Middle Rocky Mountain lows 122
Convectional theory 51
Convective rains 113–115
Countercurrent theory 52
Cox, Prof. H. J., member of board, author of Chapter VI 143
Chapter VII 177
Chapter XI 293
contributes article on storm winds in Upper Lakes, Chapter VIII 248
rule for rain in connection with general frosts 138
regarding influence of temperature 138
Cranberry marshes, frost forecasts for 203–207
Crescent-shaped lows 93, 94, 304
Cyclones. (*See also* Lows.)
barometer level in 94, 103, 112
duration of winds in 56
extratropical, convection in 57
defined 53
direction of movement of 53
direction of winds in 56
frequency of 55
hypotheses as to origin of—
(1) convectional 51
(2) driven eddy 52
(3) countercurrent 52
maximum frequency, locus of 53
migratory 60
velocity of travel of 55
velocity of winds in 57, 58
geographic origin of 70
inception of wind circulation in 26
permanent 59
semipermanent 58
relation of, to wind circulation, theory of—
(1) nonrotating earth (first stage) 28
(2) rotating earth (second stage) 28
(3) rotating earth (third stage) 29
(4) rotating earth, equilibrium stage 29
tropical, and extratropical, distinction between 48
tropical, defined 47

Digitized by Google

Page.
Cyclones, tropical, direction of travel of..... 49
winds in..... 49
energy of..... 50, 51
origin and maintenance of..... 49
place of occurrence of..... 48
size and shape of..... 48
velocity of travel of..... 49
winds in..... 49

Davis, Prof. (W. M.), discussion of hypotheses as to origin of cyclones..... 52
Deflective force, due to earth's rotation..... 18
numerical values of..... 24
Denver district, forecasts of weather and temperature in..... 320–326
cold waves in..... 171
frosts in..... 209
Devereaux, W. C., prepared Fig. 30..... 89
Dew point, relation of, to frost forecasting..... 202
Dunwoody (Lieut. H. H. C.), work cited..... 231
Depressions, V-shaped (*see also* Lows)..... 75, 94

East Gulf lows..... 125
Eddies. (*See* Winds.)
Eddy, driven, theory..... 52
Espy (J. P.), rise of barometer as an indication of approaching storm..... 231

Fassig, Prof. O. L., work cited..... 233
Florida, forecasting frosts in..... 190
Foehn, or chinook. (*See* Winds.)
Fog, defined..... 260
frequency of, on Atlantic coast, diagram of..... 265
Gulf coast, diagram of..... 269, 270
Pacific coast..... 273
geographic distribution of..... 266
meteorological conditions precedent to formation of..... 261–263, 268
seasonal distribution of..... 261, 266
Forecast districts, boundaries of. (*See* Frontispiece.)
Forecasting. (*See also* under Cold waves, Frosts, High winds, Fog, Snow, Sleet, Thunderstorms, Weather, and Temperature.)
Frankenfield, Prof. Harry C., member of board, author of Chapter IX, article on storm winds in Chapter VIII.
precept as to failure of rain in southwest lows... 283
Frontiers, of Washington district..... 231–235
Frost, and dewpoint, relation between dewpoint and minimum temperature of succeeding night..... 202
and median temperature, relation between..... 201
charts of, in United States..... 180–185
damage by..... 178
forecasting of..... 196–199
in California..... 214
cranberry marshes..... 203, 207
Florida..... 190
Gulf coast region..... 191, 206
Northern sections..... 191
North Pacific States..... 211
Pacific coast districts..... 188

Digitized by Google

Page.
Frost, forecasting of, in Rocky Mountain region 194, 209
West Gulf region 208
Wisconsin, in summer 195
formation of 177
occurrence of, effect of environment upon 179
topography upon 185
relation between nature of soil and 187
reporting occurrence of, difficulties encountered 200

Galveston, convectional showers at 114
Garriott, Edward B., cold waves, movement of 154
long range weather forecasting 341
movement of West India hurricanes 231–232
rule regarding influence of temperature 138
Glassford (Col. W. A.), rule regarding influence of temperature 138
Glossary 349
Gradient velocity 21, 221
Gradients, barometric 350
Great Basin highs 132
forecasting value of 134
Great Lakes, effect of, on lows and highs 298, 306
influence of, on cold waves 151
frosts 185, 186
Gulf Coast, fog, frequency on, diagram of 270
Gulf Coast region, forecasting frost in 191, 208
Guilbert, Gabriel, rules for forecasting 140

Hammon, Prof. W. H., forecasts of 335
Hanzlik (S.), position of katallobars 81
relation between pressure gradient and velocity of lows 98
Heated spells, forecasting break in, Chicago district 314
Henry, Prof. Alfred J., chairman of board, author of Chapters IV, V, and X; article on Thunderstorms, in Chapter IX.
High. (*See also* Anticyclones.)
defined 71
influence of, in blocking advance of low 107
Highs, classified:
(1) permanent 60
(2) semipermanent 64
(3) migratory 64
Highs, in their temperature relations 135
Atlantic, occurrence of thunderstorms in connection with 277
continuous rise of pressure at center of 128
disintegration of 136
fast moving, configuration of isobars in:
(1) circular or oval 130
(2) wedge-shaped 130
fast moving, not associated with marked fall in temperature 129
forecasting precepts from 139
Great Basin 132
forecasting value of 134
Hudson Bay 135
ill-defined 96
Lake region, of spring 134, 347
large central 347

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Page.
Highs, movement of ... 127, 159
and attendant precipitation ... 305
as determined by anallobars ... 90
in Chicago district ... 305
in Lake region in spring ... 306
in spring and autumn ... 195
precipitation, in southwest quadrant of ... 137, 287, 300
on southern side of ... 286
pseudo ... 130
reenforced ... 130–131
relation of to anallobars ... 80
stagnant weather conditions prevailing in ... 131–135
trend of isobars in ... 137
volocity of movement of ... 64
well-defined ... 96
wind circulation in ... 30
velocity in ... 64, 65
winter plateau ... 347
with increasing pressure at center ... 130
Hot spells, forecasting breaking up of ... 290–291, 314
Hot winds ... 316
Hudson Bay highs ... 135
Humidity, relative, a factor in frost prediction ... 203
Humphreys, Prof. Wm. J., contributes Chapter II ... 33
Hurricanes, West Indian, movement of ... 230–232

Inversion. (*See* Temperature.)
Isobars, trend of, as influencing precipitation ... 300–301
temperature ... 137, 160
types of, fundamental:
(1) cyclone ... 75
(2) secondary ... 75
(3) V-shaped depression ... 75
(4) anticyclone ... 75
(5) straight isobars ... 75
(6) col ... 75

Katallobar ... 79
forecasting precepts from ... 88, 89
movement of ... 84, 85, 86
position of center with respect to center of low ... 84
Kite flights, in connection with slow-moving low ... 108

Lake region, eastward drift of atmosphere in ... 99
highs, of spring ... 134, 347
Long-range forecasts ... 341, 347
Lows. (*See also* Cyclones) ... 71
aleutian ... 59
icelandic ... 58
advance of, blocked by high over Canadian Maritime Provinces. 105, 107, 283
blocked by rising pressure ... 97, 105, 283
average speed of ... 97, 98
average track of, January ... 95
July ... 95
blocking of ... 107

Digitized by Google

Page.
Lows, characteristics of, in Washington district..... 281–285
circular, movement of..... 100–101
classified:
(1) Alberta..... 120–121
(2) Central Group..... 122
(3) Circular..... 101–101
(4) Colorado, or Middle Rocky Mountain..... 122
(5) Cresent-shaped..... 93, 94, 304
(6) East Gulf..... 125
(7) Northern Rocky Mountain..... 121
(8) North Pacific..... 116–120
(9) South Atlantic States..... 125
(10) South Pacific States..... 119
(11) Southwest..... 123–124
(12) Texas..... 123, 124
(13) V-shaped depressions..... 75, 93
convection in..... 57
deep..... 93, 94
development of, south of and between two highs..... 223
a ridge of high pressure..... 224
in southern end of barometric trough..... 224
direction of winds in..... 56
discussion of, by groups..... 116–126
disintegration of..... 101
"dry", in Oklahoma..... 111
duration of winds in..... 56
erratic movement of..... 105, 106
form of isobars in..... 75, 93
frequency of..... 55
geographic origin of..... 70
inception of wind circulation in..... 26
increase or decrease in intensity of..... 222, 223, 229, 230
intensity of, as affected by direction of movement..... 109–110
long, oval-shaped, movement of..... 101
migratory..... 60
movement of (*see also* Slow moving lows and rapid moving lows)..... 94, 96, 100, 101, 158, 170, 171, 294
movement of, as controlled by upper currents..... 95
indicated by katallobars..... 89, 90, 96
North Pacific, forecasting from..... 119
interrupted in advance inland..... 116
path of, in May..... 118
January..... 118–119
pressure fall in, interrupted..... 116–117
orographic control of movement of..... 103
paths of slow-moving..... 105–107
permanent..... 59
precipitation in connection with..... 111
rapidly moving..... 98
northern..... 100
rising pressure in, control of movement by..... 97, 105, 108
progress to northeast barred by..... 97, 105
semipermanent..... 58

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Pages.
Lows, slow moving 101, 102, 103, 104, 105
South Atlantic, discussion of 126
speed and direction of movement of, as indicated by surface observations 96, 97
velocity of travel of 55
wind circulation in, nonrotating earth 28
rotating earth (second stage) 28
(third stage) 29
equilibrium stage 29
wind velocity in 57, 58

Martin, Howard H., rain forecasts for northeastern Texas 114
Marvin, Prof. Chas. F., contributes Chapter I 15
Modena, Utah, cold waves at 154
Mount Tamalpais, data of, in forecasting 247, 338
Weather, kite flights at 108
Milham, Prof. (W. I.), quoted 52

New England, cold waves in 169
New Orleans district, forecasts of weather and temperature in 317–319
cold waves in 170
frosts in 208
high winds in 239
Nomenclature 79
Northern Rocky Mountain region, lows of 121
precipitation forecasts for 307
Northers 233
North Pacific forecast district, cold waves in 172
frost warnings in 211
weather and temperature forecasts in 327
high winds in 244
highs and lows, action of, in 116–120

O'Gara, P. J., dewpoint in frost forecasting 202
Oklahoma, "dry" lows in 111
Pacific coast, fog frequency on 273
forecast districts. (*See* Portland and San Francisco districts.)
Pague, B. S., cited 329
Plateau highs, of winter 347
region, cold waves in 154
Portland, Oreg., district, forecasts of:
cold waves 172
frosts 211
high winds 244
weather and temperature 331–333
Precipitation, as conditioned upon level of barometer 112, 113
associated with form of isobars 112
convective 113–115
in the Southwest 114–115
distribution of, with relation to thunderstorms 275
forecasts of, slow to begin on warm side of a trough 138–139
in northern Rocky Mountains 307
in form of snow and sleet 308
precepts from clouds 287
occurrence of, in southwest quadrant of high 137
on underside of high 286

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Page.
Precipitation, occurrence of, as conditioned on movement of highs (in Chicago district) 305
in form of snow or sleet 308
connection with general frosts 138
lows 111
northern Rocky Mountain region 307
relative position of low and high conducive to 111
Pressure, changes in, auxiliary charts of 77
charts of, defined 72
relation to temperature changes 73
uncertainty in interpretation of 80
four-hour charts of 225–229
distribution of, a characteristic form in North Pacific lows 120
as indicating development of lows 223
relative to movement of lows 96, 102, 283
occurrence of convective rains 113–115
thunderstorms 275–276
rising pressure blocking advance of lows 105, 107, 283
with altitude 40
fluctuations in:
(1) periodic 77, 78
(2) nonperiodic 78
gradient 20
value of, in forecasting 24
level of, in a cyclone, relation to clearing weather 344
relations, as affecting weather in the United States 345

Rain. (*See* Precipitation.)
Convective 113–115
Rocky Mountain region, forecasting frost in 194, 209
Roseburg, Oreg., barograph trace at 117

Saddle, a form of barometric depression 75
Sanding, of soil, effect of, on frost occurrence 187
San Francisco district, forecasts in:
cold waves 174
frost 214
high winds 246
weather and temperature 335–339
Sea swells 238
Secondary (*see also* Isobars, fundamental types of) 75
Shaw (Sir Wm. Napier), and Lempfert (R. G. K.), quoted 97
Showers, convectional, at Galveston 114
Sleet 257
and snow, forecasts of 308
geographical distribution of 258
occurrence of, meteorological conditions favorable to 259–260
or heavy snow, difference between antecedent conditions 256
seasonal distribution of 259
Slow-moving lows, kite-flight observations in connection with 108
Smith, John W., contributes article on cold waves 169
frost warnings 207
Smith, J. Warren., frost forecasting 202
Snow cover, influence of, upon air temperatures 315

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Page.
Snow, heavy. or sleet, difference between antecedent conditions..... 256
forecasts of..... 308
forecasting of..... 253, 256
meteorological conditions preceding..... 254
seasonal distribution of..... 254
Soil, character of, as contributing to occurrence of frost..... 187
South Pacific forecast.district. (*See* San Francisco district.)
Atlantic lows..... 125–126
Southwest lows..... 123, 124
Stewart, W. P., quoted..... 114

Temperature, absolute minimum in United States..... 144–146
as influencing precipitation..... 284
changes, charts of, defined..... 72
distribution, seasonal, with altitude..... 38
in latitude and with altitude..... 40
forecasts of, breaking up of hot spells..... 290–291, 314
relation of, to anallobars..... 82
forecasting changes in..... 135–136
discussed by districts:
Chicago..... 311–315
Denver..... 323–326
New Orleans..... 318–319
Portland..... 331–333
San Francisco..... 338
Washington..... 288–291
summer..... 290–291
winter..... 135, 288, 289
use of charts in..... 316
influence of, movement of highs on..... 313–314
on horizontal pressure gradients..... 39
of snow cover on..... 315
inversion, at surface..... 260, 276
between Mount Tamalpais and San Francisco..... 338
normal, 8 a. m. third decade, January..... 147
relation between that of air and vegetation..... 179
of pressure changes to..... 72–73
of, to precipitation..... 304
value of, in forecasting path of lows..... 138
Temperatures, mean land and water..... 267, 271
high, on south side of trough, inimical to precipitation..... 138
night, variation in..... 200
Tendency, barometric, defined..... 79
Terminology..... 74
Texas lows..... 123, 124
Texas, rain forecasts for northeastern..... 114
Thermometer exposure, influence of, upon recorded temperatures..... 152
Thunderstorms..... 274–278, 310
diurnal variation in..... 275
generated by excessive temperature and high humidity..... 277
in connection with Atlantic highs..... 277
in winter..... 278
relation of, to pressure distribution..... 275
seasonal and geographic distribution of..... 275

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Page.
Tornadoes (*see also* Winds)..... 65, 310
cause of..... 67
why peculiar to United States..... 68
Troughs, barometric, immature, defined..... 100
precipitation slow to begin on warm side of..... 138–139
rapid movement of..... 99–100

Upper air currents, control of movement of lows by..... 95
Upper Lakes, storm winds on..... 248

V-shaped depressions..... 75–93

Walz, Prof. F. J., application of Guilbert's rules to forecasting..... 140
Warnings, cold wave, effect of variation in verification..... 153
verification of..... 145
frost, when required..... 203
storm, basis of issue of..... 218
details to be given in..... 219
time of display of..... 218
Washington forecast district, forecasts in. (*See* Cold waves, Frosts, Heavy snow, High winds, Thunderstorms, Weather and temperature.)
Washington forecast district, general characteristics of lows in..... 281–285
frontiers of..... 281
Water, effect of, upon air temperatures..... 151, 185
Waterspouts..... 68
Weather Bureau Bulletin T, résumé from..... 204–207
Weather and temperature, forecasts of, by districts:
Chicago..... 293
Denver..... 320
New Orleans..... 317
Portland, Oreg..... 327
San Francisco..... 335
Washington..... 279
Weather and temperature, forecasts of definition of terms and periods used..... 279
long range..... 341–347
seasonal influences in..... 280
Weather forecasting, synoptic weather charts basis of all..... 69
preliminary statement..... 69
map, description of..... 25
issue of storm warnings based on..... 69
Wedge-shaped isobars. (*See* Isobars and highs.)
Weekly weather forecasts, sample of..... 342
West Gulf region. (*See* New Orleans forecast district.)
Willson, Geo. H., contributes article on cold waves in San Francisco district.. 174
frost warnings in San Francisco district..... 214
weather and temperature forecasts in San Francisco district..... 335
Wind systems, cyclonic and anticyclonic..... 25, 32, 49, 64, 220
Winds, antitrade..... 46, 47
character of, at different altitudes..... 16
chinook, or foehn..... 65, 332
direction and velocity of, automatic adjustment of..... 21
Doldrums, seasonal, latitude, limits of..... 46
equatorial, direction of..... 41

33692—16——24

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Page.
Winds, force of, Beaufort scale 221
forces that cause and modify 17, 22
general changes in, with elevation 33, 34
gradient-velocity, defined 21
high. (*See* Warnings, storm.)
hot 316
hurricane. (*See* Hurricanes.)
monsoon 42, 43
planetary 33
relation of, to forecasting weather and temperature 139
seasonal velocities, with altitude 37
secondary, classified:
(1) eddies 65
(2) foehn, or chinook 65
(3) tornadoes 66
storm, Atlantic coast 235–237
Great Lakes 231, 248, 252
Gulf 239, 241
Pacific coast 244, 248
increase or decrease in intensity of 218, 222, 223
trade, seasonal latitude limits of 45, 46
velocity of, at different elevations 17, 35, 36
in anticyclones 64, 65
in connection with barometric gradients 140, 222
latitude of greatest 41
relation of, to latitude 17
season of greatest 41
Winnemucca, Nev., cold waves in 154
Winnipeg, Manitoba, weather statistics for 133
Wisconsin, forecasting summer frosts in 195

Zones, cold wave, for verification 43

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